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Institute of Polar Studies

Report No. 7

Glaciological Studies on the McMurdo-South Pole Traverse, 1960-1961

by

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Prepared for

National Science Foundation

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The Ohio State University
Research Foundation
Columbus 12, Ohio

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Submitted by Richard P. Goldthwait, Director
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ABSTRACT

Studies of snow stratigraphy indicate that the mass accumulation between Victoria Land Plateau (78° 02' S, 154° 22' E) and the South Pole is approximately 4.5 $g.cm^{-2}yr^{-1}$ (±20%), which is one-half the amount determined previously for the same region. The rate of mass accumulation decreases from south to north, a trend opposite to that reported in the literature. This can be explained in terms of the known pattern of atmospheric circulation and topography.

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GLACIOLOGICAL STUDIES ON THE McMURDO-SOUTH POLE TRAVERSE, 1960-1961

INTRODUCTION

An eight-man party made studies on seismology, glaciology, and related disciplines along the route of an oversnow traverse between McMurdo Sound and the geographical South Pole (Fig. 1).

After preparation of the vehicles at the U. S. Naval Air Facility at McMurdo Sound, the traverse party departed on December 10, 1960, and arrived at the South Pole on February 12, 1961. The distance of 2350 km was covered with practically no delays, except for relatively slow traveling on the Skelton Glacier.

The participants in each discipline were as follows:

Geophysics: A. P. Crary, party leader (National Science Foundation)
E. S. Robinson (University of Wisconsin)
A. Meyer (U. S. Coast and Geodetic Survey)

Glaciology: M. B. Giovinetto (The Ohio State University)
J. Zahn (The Ohio State University)
E. Evteev (Exchange scientist from U.S.S.R.)

Traverse Engineering: J. Long (University of Wisconsin)
R. Ash (University of Wisconsin)

The vehicles used were three diesel-powered Tucker Sno-Cat units, two Model 843 with a total weight of eleven tons each and one Model 743 with a total weight of six tons; two Rolli-Trailer units with a total weight of seventeen tons each; and four, one-ton capacity sledges. Crary and Robinson (1962, p. 291-295) described the outline of the scientific program, the traverse procedures and logistics.

The glaciological program is outlined as follows:

1) Determination of surface slope at the major stations (100 to 112, and South Pole).

2) Studies of density, temperature, and hardness of near-surface snow from 50-cm snow pits at minor stations (each 5 km between major stations).

3) Detailed studies of general stratigraphy in 2-m snow pits for determining annual accumulation at 14 stations (100 to South Pole).

4) Remeasurement of snow accumulation at stake networks emplaced in 1958-59 at Stations 72, 100, and South Pole.

5) Collection of samples for radio-isotope measurement in near-surface layers at Stations 106 and South Pole.

6) Coring and studies of density, stratigraphy, and temperature at 5- and 10-m levels in 10-m hand-drilled holes from Stations 101 and 112.

7) Measurement of temperature at a depth of 34 m in seismic shot holes at Stations 105 to 112.

8) Studies of general sastrugi patterns and amplitudes at all minor stations.

9) Surface meteorological observations at 0000, 0600, and 1900 GMT, and hourly measurements of air temperature and wind speed and direction during traveling periods.

This report discusses in particular the results of the studies indicated as 3) and 4). The observations indicated as 7), 8), and 9) are evaluated in the first chapter. The measurements of background radioactivity 5) are in progress. Current work by Crary and Evteev concerns the studies indicated as 1), 2), and 6).

For the first 500 km, between NAF McMurdo and Station 100, the traverse party followed approximately the route of earlier expeditions. As this segment of the route had been traveled before by the Commonwealth Trans-Antarctic Expedition 1957-58 (TAE), by the U. S. Little America - Victoria Land Traverse 1958-59, and by the U. S. Victoria Land Traverse 1959-60 and had been studied by the traverse glaciologists earlier, our observations started at Station 100, except for snow accumulation measurements which were made at Station 72.

PRELIMINARY CONSIDERATIONS ON TERRAIN AND WEATHER

Mean annual air temperature and elevations

In Table I the coordinates of each major station are shown together with the elevations and deep snow temperatures; the latter give a figure close to the mean annual air temperature.

Because of the variation of temperature with latitude, the temperature data shown in Table I were used together with data from other expeditions (Bogoslovsky, 1958, p. 293; Lister, 1959, p. 346; Stuart and

Table I. Location and elevation of major stations, dates when the studies were made, and approximate mean annual air temperature

Station	Latitude	Longitude	Elevation	Date	Depth, m	Deep Snow Temperature °C
72	78° 02' S	158° 25' E	2366	25-12-60	> 10	-41.5*
100	78 02	154 22	2282	28-12-60	> 10	-44.0**
101	78 36	149 00	2372	2- 1-61	10	-46.6
102	79 12	143 12	2404	6- 1-61	10	-47.1
103	80 10	139 02	2402	9- 1-61	10	-45.2
104	80 59	134 20	2580	11- 1-61	10	-45.8
105	82 19	130 28	2754	14- 1-61	34	-48.7
106	83 26	124 48	2888	18- 1-61	34	-48.9
107	84 18	132 31	2795	21- 1-61	34	-48.15
108	85 16	140 48	2821	25- 1-61	34	-46.6
109	86 07	147 30	2849	31- 1-61	34	-45.6
110	87 07	156 25	2960	3- 2-61	34	-47.1
111	88 07	170 30	3094	6- 2-61	34	-48.7
112	88 39	157 30	3007	10- 2-61	34	-50.9
South Pole	90 00		2800	12- 2-61	12	-50.8*

*Adopted from other studies
**Interpolated

Heine, 1961a, Plate 1) to complete a series of stations distributed east to west instead of north to south, thereby eliminating the need of correction for latitude.

The following approximate variations of air temperature with elevation were obtained: at 78° S, between 2186 and 3540 m, 1.1° C/100 m; at 83° S, between 2697 and 3710 m, 1.05° C/100 m. In other sectors of East Antarctica, Bogoslovsky (1958, p. 293) and Mellor (1960, p. 774) determined rates of approximately 1.0° C/100 m for regions between 0-2000 m, and approximately 1.25° C/100 m for regions between 2000-3500 m. Lorius (1962, p. 181) determined a rate of 1.0° C/100 m along longitude 142° E between the latitudes 67° and 78° S (0-2700 m). In general, the rates determined for several regions of East Antarctica lie in the same order of magnitude.

The snow temperature measured at depths of 10 and 34 m were used to place the -45° and -50° C surface isotherms (Fig. 1), complementing data of the investigators mentioned above. The noticeable conformity between these isotherms and the contour lines would be expected from the normal adiabatic lapse rate.

Surface features and wind direction

Observations on the orientation and characteristics of surface features were similar to those reported by Lister (1959, p. 347) for the same region. The orientation of surface features observed by the glaciologists of the U. S. parties which visited Victoria Land (Stuart and Heine, 1961a, Plate 1), the area south of Byrd Station (Long, personal communication) and the Ross and Filchner Ice Shelves (compiled by W. Vickers, Institute of Polar Studies office memo), complete a general pattern of surface winds across Antarctica (Fig. 1).

Several investigators have established that storm winds are responsible for the preferred orientation of surface features. At the South Pole and in the northern region covered by the traverse (for the latter there are summer data only), storm winds are from the same quadrant as the prevailing surface winds. Along the route of the traverse the direction of the observed surface winds was always coincident within 10 or 20° with the orientation of the surface features, except when the wind speed was less than 2 or 3 knots. The dry snow cover of the region covered by the traverse is more susceptible to corrasion at the relatively mild speed of katabatic winds than the snow cover of regions where relatively high winter temperatures and summer melt increase the granular cohesion of the snow cover. This snow cover is sculptured mainly by strong storm winds. Later surface winds contribute their effects with recognizable minor features such as deflation pockets and deposition patches in the zones of the "wind shadow" caused by the large sastrugi. On the plateau the orientation of minor features does not depart greatly from the orientation of sastrugi. Therefore, we can assume that in the plateau the orientation of surface features indicates the predominant direction of winds at the surface.

The westerly deviation of the katabatic winds from the direction of greatest slope, and the nature and magnitude of topographic and atmospheric factors affecting it have been evaluated by Ball (1960, p. 9-16). These factors could reasonably explain the departure of about 45° which is observed north of 78° S (along 140°E), south of Byrd Station and between South Ice and the South Pole. However, a more suitable explanation is needed to account for the observed surface wind direction along 140°E between 78° S and 90° S, where the predominant surface winds deviate 60° or more from the direction of greatest slope. In fact, the winds are almost parallel to the contour lines in the region of Stations 104 to 102, and apparently move up-slope in the region of the Stations South Pole and 112. To what extent the anti-clockwise circulation around the anticyclone of East Antarctica can divert the direction of katabatic flow is not known. A trough between the region covered by the traverse and the mountain ridges west of the Ross Ice Shelf could exert a deviating influence; Lamb (1959, p. 356) favors this argument as an explanation for the phenomena along TAE's route. The key to understanding these deviations may be found in the synoptic patterns for the region based on upper air data from stations such as NAF McMurdo, South Pole, and Vostok. Rubin (1960a, p. 69) has indicated that cyclonic storms are an additional factor in the alteration of the direction of surface winds in a coastal slope.

Glazed surfaces and fissures

Along the route of the TAE, Lister (1959, p. 347) reported glazed surfaces between 81° and 88° S (East longitude) and Stuart and Heine (1961a, p. 5 and 25-26) described glazed surfaces and fissures which they encountered between Stations 72 (or Plateau Depot) and 100 (their 84). Patches of glazed surface were observed intermittently between Stations 72 and 110; their frequency increased nearer Station 100. They had remained exposed for at least a year since vehicle tracks made the previous summer between Stations 72 and 100 could be seen on their surface. The nature of these features is not fully understood. The fissures are most visible in the glazed surfaces. Since these areas are not covered by snow accumulation, the fissures are visible. However, this does not imply that fissures occur only in the extremely hard strata of which the glazed patches are the surface expression (see APPENDIX A).

Glazed surfaces and accumulation

The number of glazed surfaces per unit of area increased from a point approximately half-way between Stations 72 and 100 to the westernmost point reached by the 1958-59 Little America - Victoria Land Traverse (S. Den Hartog, personal communication). This increase indicates a decreasing rate of mass accumulation toward the west along 78° S. The observed stratigraphic characteristics in the region supports a decrease in the rate of mass accumulation toward the west. Other things being equal, it is clear that as the rate of accumulation decreases more annual layers are subjected to annual and seasonal air temperature variations; and, because of this, sublimation effects have reached extreme development (Giovinetto, 1960a, p. 6; 1961, p. 389). As accumulation decreases toward the west it is reasonable that sublimation effects increase. Stratigraphic descriptions by Den Hartog (1959, p. 68-101) bear this out.

Environment and its effects on stratigraphy

The environment of the region between Station 72 and the South Pole can be described in general terms on the basis of the preceding information and meteorological data. The latter were collected at the South Pole by U. S. Weather Bureau personnel; at Station 72 by the U. S. Navy crews who for several seasons landed there in supply missions between October and March, and west and north of Station 72 by personnel of both Victoria Land traverses. These are the chief characteristics of the area:

1) High elevation: 2250 to 3100 m above sea level.

2) Featureless topography with a gentle slope, except for local undulations and other microrelief.

3) Mean annual air temperature between -45°C and -50°C.

4) Large annual range of air temperature. The highest air temperatures close to -15°C were observed during January; from these and the annual mean temperatures, it can be inferred that minimum temperatures close to -70°C are reached during the winter.

5) Wind direction at a given location generally is from a determined quadrant, and speed generally is above 10 knots. Because of this and the relatively constant angle of incidence (horizontal) of drifting particles, corrasion is deep. Wind speed and direction have a direct effect on the magnitude of eolian features which have been described profusely in the literature.

6) Simultaneous snow deposition and deflation. After a given time an area may have registered a net gain or loss of snow, but particular points within the area will show gains and losses. Both may be several times greater than the observed mean.

7) Cloud cover ratio is higher during the summer than in winter. This phenomenon has been observed at the South Pole for several years. Judging from summer observations along the routes of traverses, the annual mean may be less than 5/10.

8) Precipitation, generally in the form of columnar ice crystals, is seldom larger than 1 mm.

9) Balance of solar radiation at the surface is negative. The high latitude of the region, which results in a low angle of incidence of solar radiation, and the high albedo of the dry powder snow at the surface account for this (Loewe, 1955, p. 661; Hanson, 1961, p. 174).

Many of these environmental factors determine the definition of seasonal layering and make identification difficult because:

1) Snow is homogeneous due to drifting and wind packing.

2) Seasonal layers are thin and irregularly deposited.

3) All layers are affected by sublimation (either phase) throughout several years, and the originally-faint horizons are obliterated.

4) Summer melt is negligible (dry snow facies; Benson, 1959, p. 17-21).

However, summer and winter weather and sun radiation conditions differ sharply, producing relatively large changes in the snow cover. These changes have been evaluated and used with different degrees of success by many investigators.

STRATIGRAPHIC STUDIES

Methods of study

There is no summer melting in the region (Table I). Sorge (1935, p. 110-121) was the first to discuss the criteria for the identification of summer and winter layers for a locale where snow of the dry facies is predominant. Since then, investigators have determined patterns in stratigraphic profiles where there is no summer melting and annual accumulation is small, but definite criteria have not been enunciated; among the several investigators are Lister (1956, p. 230-237; 1959, p. 344), Schytt (1958, p. 76-110), Benson, 1959, 7th data sheet), Giovinetto (1960a, p. 5-73; 1960b, Tables 1 "A" through 1 "C"), Kotliakov (1961a, Fig. 74; 1961b, Fig. 1), Gow (1961, p. 9).

Kotliakov (1961b, p. 15-18) discussed the seasonal structure of the strata in the central plateau of East Antarctica, based on observations made at Vostok 1 and Komsomol'skaya Stations. The quantitative expression of the divergences he found in the physical and mechanical properties of seasonal snow appear in Table II. Grain size and compaction, the latter reflection in the air permeability coefficient, are the two major criteria for the identification of seasonal layers. Despite attempts such as Kotliakov's, the determination of the seasonal nature of stratigraphic elements in sections studied on a traverse remains subjective in character because much of it depends on the on-site evaluation of the annual pattern of sublimation effects.

During the traverse shallow sections were studied because a few meters of the strata comprise several annual accumulation layers, thereby given a representative mean, and because the observer could then extend his observations on the lateral projections of a given layer in the available time. This is a recommended procedure in view of the relatively large areal variability of snow deposition, to be discussed later.

In APPENDIX B the strata from each station are shown in situ and some of the more relevant characteristics are represented with symbols. The key to the graphs and other pertinent information are offered at the beginning of the APPENDIX. The results are summarized in Table III.

Generally, the criteria for the identification of annual layers are based on stratigraphic patterns in sections where snow accumulation data are available from stake measurements. The stakes at Station 100 provided the control for interpreting the snow stratigraphy in the region.

Other methods of identifying annual layers, or dated horizons at given years, are oxygen-isotope ratios and changes in background radioactivity. Studies of oxygen-isotope ratio for several locations in Antarctica by Sharp and Epstein (1962, p. 273-285) give rates of accumulation 50% to 100% larger than those indicated by stratigraphic interpretation. Before generalizing on this, however, more data are needed both in number of sampling sites and depth coverage to determine the real significance of the results of these studies. The last statement also applies to the results of studies made on samples collected for radioisotope measurement in near-surface layers at Station 106 (J. Mortensen and C. Bull, personal communication).

Samples for radio-isotope measurements were collected in a pit to a depth of 2.4 m at the South Pole. Gow (personal communication) had made a stratigraphic interpretation at this pit, and placed the 1954 accumulation layer at a depth between 1.15 and 1.27 m. The five-year record of snow accumulation measurements at a stake network show his interpretation to be reasonable; therefore, it shall be interesting to compare the results of the analysis of the South Pole samples, which are in progress, with those from Station 106.

Table II. Physical and mechanical properties of winter and summer snow*

Physical and Mechanical Properties	Winter	Summer	Difference, Winter-Summer	Divergence, Winter-Summer, %
		Vostok-1		
Number of layers	39	34	-	-
Weight by volume (g/cm^3)	0.437	0.402	0.035	8
Hardness H (kg/cm^2)	8.3	7.5	0.8	9.6
Size of grains S (mm)	0.60	0.81	-0.21	35
Height of capillary rise h (cm)	4.0	2.8	1.2	30
Maximum water-retaining capacity m (%)	75.9	65.5	10.4	13.7
Air permeability coefficient k (cm/sec)	104.5	199.9	-95.4	91
		Komsomol'skaya		
Number of layers	38	33	-	-
Weight by volume (g/cm^3)	0.410	0.399	0.011	2.7
Hardness H (kg/cm^2)	4.9	4.4	0.5	10
Size of grains S (mm)	0.57	0.74	-0.74	29.8
Height of capillary rise h (cm)	3.8	2.8	1.0	26
Maximum water-retaining capacity m (%)	78.8	71.0	7.9	9.9
Air permeability coefficient k (cm/sec)	113.5	182.1	-68.6	61

*After Kotliakov, 1961, p. 16; translated by S. Sorgenstein

Table III. Mean annual mass accumulation determined from stratigraphic studies

Station	Period	Possible Error (Year)	Total Snow Thickness (cm)	Mean Specific Gravity ($g.cm^{-3}$)	Total Accumulation ($g.cm^{-2}$)	Number of Years	Mean Accumulation ($g.cm^{-2}y^{-1}$)	Range* of Mean Accumulation ($g.cm^{-2}y^{-1}$)	Gross Variability (%, sd. dev.)
100-1	1960-54	+2	45.0	.35	15.8	7	2.3	1.8-2.3	113
100-2	1960-54	±2	42.5	.35	14.9	7	2.1	1.7-3.0	43
100-3	1960-54	-2	46.5	.35	16.3	7	2.3	2.3-3.3	58
101	1960-54	±2	82.5	.37	30.5	7	4.4	3.4-6.1	48
101(a,b)	before 1954	-	141.5	.41	58.0	8 to 14	-	4.1-7.3	-
102	1960-55	±2	62.5	.39	24.4	6	4.1	3.1-6.1	34
102(a,b)	before 1955	-	159.5	.39	62.2	10 to 15	-	4.1-6.2	-
103	1960-51	±2	71.0	.39	27.7	10	2.8	2.3-3.5	61
104	1960-	±1	79.5	.42	33.4	9	3.7	3.3-4.2	33
105	1960-53	±1	94.5	.40	37.8	8	4.7	4.2-5.4	45
106	1960-54	±2	81.0	.39	31.6	7	4.5	3.5-6.3	57
107	1960-57	±1	40.0	.41	16.4	4	4.1	3.3-5.5	67
108	1960-48	±3	138.5	.37	51.2	13	3.9	3.2-5.1	25
109	1960-51	±2	104.5	.37	38.7	10	3.7	3.2-4.8	37
110	1960-45	±4	203.0	.41	83.2	16	5.2	4.2-6.9	35
111	1960-50	±2	199.0	.37	73.6	11	6.7	5.7-8.2	27
112	1960-48	±4	209.5	.37	77.5	13	6.0	4.6-8.6	45
South Pole	1960-55	-	112.0	.36	40.3	6	6.8	1.1-16.2	78**

*Considering the possible error.
**Study site was selected because of highest variability.

MASS ACCUMULATION

General

The main purpose of the study of snow stratigraphy was to determine the rate of water accumulation at each major station. The region covered by the McMurdo-South Pole traverse is practically the same region studied by Lister (1959, p. 343-348) early in 1958 (Fig. 2). He determined an annual accumulation between 6 and 13 $g.cm^{-2}$ for stations 36 to 53 along TAE's route, with a possible error of ±50%. The results of the present study indicate that the rate of annual accumulation is between 2 and 7 $g.cm^{-2}$ ±20% (Table III). The magnitude of the possible error could be enlarged by a small amount considering the chances of missing an annual layer because it is non-existent in a particular stratigraphic section (p. 13).

The rates of accumulation determined between Station 100 and the South Pole are compared with Lister's rates of accumulation between his Stations 36 and 53 in Figure 3. The mean accumulation between Stations 100 and the South Pole is approximately one-half of that between Stations 36 and 53. Undoubtedly, part of the difference in accumulation at a given latitude is due to the different location (E-W) of the traverse routes, e.g., Stations 104-106 and 45-48 are 200 km apart. However, relatively large differences exist in the rate of accumulation between Stations 100 and 53, and between 108 and 42, which almost are coincident in location. The possible errors in the interpretation of both sets of data (20% and 50%) are sufficiently large to account for the difference between Stations 108 and 42 (5 $g.cm^{-2}yr^{-1}$), but not for the difference between Stations 100 and 53 (11 $g.cm^{-2}yr^{-1}$).

Before proceeding, the variations of the rate of snow accumulation should be discussed on the basis of data obtained at stake-networks. There are variations in the rate of snow accumulation both in area and time. When considering annual layers individually, the areal variability is independent of time; the variation with time can be considered when two sets of data covering different periods are compared. Areal variability includes terms of local and regional variability. The local variability refers to the variations in thickness of a given annual snow layer such as are measured at areas covered by stake networks. The regional variability refers to the change in average thickness of an annual layer, e.g., along a given latitude or longitude.

Measurements of snow accumulation at stake networks

At three locations along the route snow accumulation has been measured at stake networks -- Stations 72 and 100, and at the South Pole (Fig. 2).

At Station 72 (Upper Skelton Cache or Plateau Depot in other publications) 22 stakes were emplaced 300 m apart on December 17, 1958, by personnel of the Little America - Victoria Land traverse 1958-59 (Crary, personal communication). Accumulation was measured at this network on November 10, 1959, by the personnel of the Victoria Land Traverse 1959-60 (Stuart and Heine, 1961a, p. 19), and again on December 26, 1960. The annual mean accumulation for the two-year period was 13.5 g.cm^{-2}; the accumulation during 1959 was 10 g.cm^{-2} and during 1960, 17 g.cm^{-2}. The local areal variability of snow accumulation was high; the standard deviation of the individual values measured at each of 22 stakes was 65% during 1959 and 41% during 1960.

At Station 100 (84 in other publications) the periods between measurements were similar to those at Station 72, the observers being the same. The mean annual accumulation measured at 32 stakes 50 m apart for two years was 1.8 g.cm^{-2}; 1.5 g.cm^{-2} for 1959 and 2.1 g.cm^{-2} for 1960. The relative standard deviation of the 32 individual values was 82% in 1959 and 158% in 1960, much larger than the relative areal variability at Station 72.

Measurement of snow accumulation at 42 stakes emplaced 300 m apart in the region of the South Pole was completed at the end of the traverse, covering the period January 27, 1958 - February 13, 1961. The network also was measured once on November 5, 1958, and again on November 4, 1959, (the last measurement was made by E. Fremow and E. Flowers, personal communication). The mean annual accumulation for the three-year period was 7.4 g.cm^{-2}, a figure equivalent to that of 7.3 g.cm^{-2} determined by stratigraphic studies for the three previous years (1955-57 inclusive) and in agreement with the mean accumulation determined for the period 1760-1957, i.e., 6.6 g.cm^{-2} (Giovinetto, 1960c, p. 64). The relative standard deviation of the 42 values measured annually was between 45% and 62%.

Areal (local) and temporal variability of mass accumulation

The South Pole data on snow accumulation obtained at the 42 stakes for three years have been used to evaluate the relationship between the local areal variability (between 45% and 62%) and the temporal variability (approximately 25%) of snow accumulation (Giovinetto, in preparation). This study indicates that approximately one-half of the gross variability (temporal plus local areal variability) for a period of 15 years at each of six stratigraphic sections is due to the local areal variability. Furthermore, the standard deviation of the two- or three-year running means obtained at each of the six stratigraphic sections generally fall within the limits of the "true" temporal variability, i.e., the gross variability less the local areal variability. Since the mean values obtained between Stations 100 and the South Pole are based on seven or more annual values (except for Station 103, 107, and the South Pole) and the mean of Stations 36 and 53 are computed from five or more values (Lister, 1960, p. 46), one can accept the comparison between both sets of data despite the large local areal variability.

It is assumed that the relation between the local areal variability and the temporal variability determined at the South Pole is extendable to the region covered by the traverse. Therefore, the temporal variability for this region is estimated as one-half of the gross variability shown in Table III, or between 15% and 55%. The problem imposed by a temporal variability of this magnitude when comparing the data by Lister and by Giovinetto is reduced because both sets of data cover periods which overlap more than 50% (TAE's data, 1957-1953; our data, 1960-1954).

Error of interpretation

Considering the relative number of stakes showing negative or no snow accumulation at Station 100 and at the South Pole, the chances of missing an annual layer because it is non-existent in a particular stratigraphic section are approximately 5% at the South Pole and 15% at Station 100. This eventuality is partly accounted for in the possible error of interpretation given by both Lister and Giovinetto. The possible error in the interpretation of a stratigraphic section can be considered as an addend to the local variability.

Regional east-west variation of mass accumulation

The other major influence in the variability of snow accumulation is regional, which in this particular case is confined to an east-west variation.

Several investigators have made stratigraphic studies and/or snow accumulation measurements in the region west of the Skelton Glacier (Figs. 2 and 4). Vickers (1958, p. 243), Lister (1960, p. 38-48), and Stuart and Heine (1961a, p. 2-4) were among the first to concern themselves with the stratigraphy, which becomes more complex further west along 78°S, as indicated by the stratigraphic descriptions of sections as far west as 131°E (Den Hartog, 1959, p. 68-101).

The following discussion considers the accumulation profiles based on stratigraphic and stake network data; the variation of accumulation in the region of the Skelton Glacier is discussed here because of convenience.

At Station 72 the stratigraphic determinations by Vickers and by Lister are in agreement with the stake measurements by Crary, and by Stuart and Heine. This agreement also is found toward the east (Skelton Glacier and Ross Ice Shelf). On the Skelton Glacier an apparent discrepancy in the rate of accumulation is noted at Stations 66 and 61, but this discrepancy is not significant because the TAE and the U. S. Victoria Land Traverse 1959-1960 followed different routes in a region where snow accumulation is notably affected by the topography of the surrounding mountains and of the glacier itself. Observations of bare ice surface in mid-December between Stations 63 and 65 indicate a low rate of accumulation and possible ablation. The reason for the bare ice at the surface is obvious if one considers the surface slope and the funnel effect of the flanking mountains on the wind (see 1:400,000 chart of the Ross Sea Region, Lands and Survey Dept., Wellington, June 1957). The combination of increased wind speed and adiabatic warming of air mass flowing down slope is a very effective ablation agent. Crary and Wilson (1961, p. 1045-1050) have elaborated on the importance of other processes, such as horizontal compressive forces, in the formation of "blue" ice areas in the same region. Farther east, Stuart and Heine's values for Stations 57 and 59 agree with Boyd's value for Station 13 (Crary and others, 1962, p. 2796).

On the plateau evidently there is a very large change in the rate of accumulation between Stations 72 and 100. How much of it is dependent on the general topography, and, in particular, on the presence of the trough between Stations 72 and 100, should be the object of a detailed study. The concern here is with the fact that west of Station 72 investigators, using the stratigraphic method, determined a rate approximately seven times larger than that measured at the stake network. The extremely small rate of accumulation is unquestionable, as shown by the two-year record of snow accumulation measurements and by the definite increase in the number of glazed surface patches per unit area west of Station 72 which were discussed earlier.

Figure 4 shows that for the region between 150° and 160° E from 77° to 79° S an east to west decrease in the annual rate of accumulation could be as high as 5 $g.cm^{-2}$100 km^{-1}. This evaluation neglects the fact that at 78° S, from Station 72 to 100, there is an anomalous decrease of 12 $g.cm^{-2}$100 km^{-1}. It seems reasonable to assume a decrease in the rate of accumulation west of Station 100 along 78° S because the patches of glazed surfaces and sublimation effects in the strata increase noticeably. However, Stuart and Heine (1961a, p. 24) report an increase in the rate of accumulation toward the northwest (from Station 502 to 510) where the strata are not affected by sublimation as much as the strata west of Station 100, and where glazed surface patches are not present. Similarly, and based on the stratigraphic studies, an increase in the rate of accumulation was determined at Stations 101 and 102 toward the southwest.

The east-west decrease of approximately 5 $g.cm^{-2}yr^{-1}$ 100 km^{-1} seems probable for the region north of 79° S between 150° and 160° E but is thought to be less intense farther west, where eventually the rate of mass accumulation should increase; at Vostok Station, Bugayev (see Dolgushin, 1961, p. 64) determined an accumulation of approximately 3.5 $g.cm^{-2}yr^{-1}$.

Based on the data presented in Figure 4 (except those from the McMurdo-South Pole Traverse) and using criteria of diverse merit, Kotliakov (1961c, facing p. 106), Cameron and Goldthwait (1961, p. 8) and Rubin (1961, p. 318) have inferred a decrease from east to west.

Portions of their data east of 160°E are presented in Figure 4. Except for the westernmost station studied by Vickers and the accumulation profile indicated by Kotliakov, there is general agreement on the magnitude of the decrease of the accumulation rate toward the west. However, at 150°E this writer indicates a rate of accumulation approximately one-half as large as those indicated by Cameron and Goldthwait and by Rubin. Kotliakov (1961c) indicates accumulation as high as 30 and 40 $g.cm^{-2}yr^{-1}$ between 160° and 165°E, but unfortunately does not specify the source of the data.

The preceding considerations concerning the influence of diverse variables in the rate of mass accumulation on the comparison between the values given by Lister and by Giovinetto (see Fig. 3) can be summarized as follows:

1. The local areal variability and the temporal variability of mass accumulation can be considered insignificant.

2. The possible interpretation error (stratigraphic sections) for each set of data is sufficiently large to account for the differences observed between corresponding stations south of 79°S.

3. The difference of 11 $g.cm^{-2}yr^{-1}$ noticed at 78°S is greatly reduced if it is considered that one half of it is due to the east-west variation in the accumulation rate. The distance between TAE's Station 53 and our Station 100 is approximately 45 km; assuming a linear decrease in the rate of mass accumulation between Stations 72 and 100 measured at the stake networks at these stations, the unexplained difference between Stations 53 and 100 may be only 6 $g.cm^{-2}yr^{-1}$. This difference is within the possible errors of interpretation (2).

North-South variation of mass accumulation

It is evident that in the region covered by the TAE and the McMurdo-South Pole Traverse, the possible error of interpretation and the east-west variations in the rate of accumulation account for the differences between the sets of data presented in Figure 3 on the basis of equal latitude. Furthermore, one must assume that the criteria of interpretation of snow stratigraphy were applied with consistency. However, the permanent sign of the difference of accumulation values between both sets of data suggest that there is a basic disagreement between them.

To account for the differences between both sets of data at 78°-82° S and 85°-87° S, the negative magnitude of Lister's possible interpretation error and the positive magnitude of Giovinetto's error must be applied consistently to the data. This procedure involves approximately one-half of the data and its application in such a large proportion seems unwarranted. Furthermore, with the exception of Station 37 (South Pole), Lister's values are higher than Giovinetto's for any given latitude, independent of the relative east-west location of TAE and our stations. Lister (1960, p. 47) adopted the South Pole value from a determination made by this writer.

The difference in slope of the least square fits computed from the data ("a" and "b" in Fig. 3) define the departure of one set from the other. In general, the rates of accumulation from the South Pole to Station 100 show a decrease of mass accumulation of 50%, whereas the rates from Station 36 to 53 show an increase of the same proportion. This difference is considered significant despite the subjectivity in interpreting the data. There is disagreement between the two determinations by a factor of 2; at the present stage of such studies a disagreement of this magnitude should be regarded as reassuring rather than otherwise.

A consideration of atmospheric circulation and topographic features reasonably explains the decrease in accumulation from the South Pole to Station 100. This is the subject of the next chapter.

It should be pointed out that Lister's value of annual accumulation for Station 36 is 9 $g.cm^{-2}$, and is 8 $g.cm^{-2}$ for Stations 38 and 39; these rates differ by less than 10% from those determined by Giovinetto for the South Pole. The difference is not significant. Moreover, Lister observed rates between 6 and 7 $g.cm^{-2}$ for Stations 33, 34, and 35. For all practical purposes the determinations of the rate of accumulation made by both investigators in the region south of 88° S are in agreement, as it also is the case in an extended area south of Ellsworth Station (Giovinetto, 1961, p. 388).

In the future, when detailed studies made by the USSR Vostok Station-South Pole Station Traverse 1959-60 are made available, it is hoped to evaluate again the significance of the data for Stations 103 to 112.

THE RATE OF MASS ACCUMULATION AND ITS RELATION TO ATMOSPHERIC CIRCULATION AND TOPOGRAPHIC FEATURES

Mass accumulation

The decrease in the rate of accumulation for the region along 140° E, from 90° S to 78° S, can be explained on the basis of atmospheric circulation and topographic features. A composite mass accumulation profile (Fig. 5) can be drawn from the Filchner Ice Shelf to the Adelie Coast, i.e., along 35° W and 140° E based on data from Lister (1960, p. 44), Lorius (1962, p. 83), Giovinetto (1961, p. 388), and Stuart and Heine, 1961b, p. 998-999).

Lister and Giovinetto independently determined the same rate of accumulation for the Filchner Ice Shelf; the departure indicated between 80° S and 82° S is expected because Lister's data corresponds to the rising ice sheet, whereas the other data correspond to the low elevation of the Ice Shelf (A-B in Fig. 5). Lister's accumulation rate along 35°W, between 82° S and 90° S is substantiated by measurements of snow accumulation at stake networks at Stations South Ice and South Pole. The rate of accumulation along 140° E between 90° S and 78° S was discussed earlier in this report. Between 71° S and the Adelie Coast, Lorius determined a rate of accumulation which, if continued toward the south, would coincide with that found at Stations 100-103; this implies an arbitrary reduction by a factor of 2 or more of Stuart and Heine's rate determined between 78° S and 71° S. Stuart and Heine (1961a, p. 3-6) stated the possibilities of large errors in the stratigraphic determinations made in the southeast to northwest leg and in the western half of the west to east leg of the Victoria Land Traverse 1959-60. In this region the extremely rough surface highly complicates the identification of annual layers. However, they believe that the results of studies made in the eastern half (east of 150° E) of the west-to-east leg are reliable because the surface in that region is smoother. These data have been adopted unaltered for Figure 6.

Figure 6 shows lines of equal accumulation (net) using the data presented in Figure 5, data for the Ross Ice Shelf (Crary and others, 1962, p. 2796), Filchner Ice Shelf and central West Antarctica (Giovinetto, 1961, p. 388) and for the northern region of Marie Byrd Land (Pirrit and Doumani, 1960, p. 10). These were completed by adopting Rubin's (1961, p. 69) lines of equal accumulation for the sector 10° E - 50° E, north of 80° S, data from the USSR Antarctic Expeditions (Dolgushin, 1961, p. 64-69), the Australian National Antarctic Research Expeditions (Mellor, 1958, p. 281; 1959, p. 524), and the Norwegian-British-Swedish Expedition (Schytt, 1958, p. 102-103). The rate of accumulation south of the Bellingshausen Sea (60 $g.cm^{-2}yr^{-1}$ line) is inferred from studies of atmospheric and topographic elements (Rubin and Giovinetto, in press); data from traverses in this region are being prepared for publication by H. Shimizu of the Institute of Polar Studies, The Ohio State University. The accumulation rates determined by Lister and by Stuart and Heine along 140° E between 88° S and 71° S are reduced arbitrarily approximately by a factor of 2, as shown in Figure 5.*

In the literature there are disagreements on the difference between gross accumulation and ablation for the steep slopes of the ice-sheet in East Antarctica. Hence, the rates of net accumulation indicated for the coastal zone are to be used with caution; in particular areas, net ablation could be indicated. In this study we are not concerned with the coastal zone of the ice sheet.

In general, Figure 6 shows that accumulation decreases toward the center of the plateau of East Antarctica (see 1:5,000,000 chart of Antarctica by the American Geographical Society, 1962). It implies that

*Snow accumulation data collected in November 1962 at 72° 38' S, 161° 32' E (19 stakes, 33.7 months; Bermel, USGS Memo) indicates a rate of mass accumulation of 6 $g/cm^{-2}yr^{-1}$ for this period, or less than one-half that determined by Stuart and Heine.

an accumulation profile drawn along any given longitude from approximately 0° eastward to 140°E will show a general decrease from the coast to approximately 80° - 85°S, and then a small increase toward 90°S (except for the region between 50° and 70°E). This relationship will be explained on the basis of atmospheric circulation and topographic features in the following section for the region covered by the McMurdo-South Pole Traverse.

Atmospheric circulation

In Antarctica the general atmospheric circulation is an important agent for the transport of mass (H_2O) to the interior of the continent. Cold air masses are deficient in moisture content but through continuous contribution their role becomes significant. The penetration of a single depression could account for a large proportion of the total annual accumulation at a given location, but this is more likely to occur in West Antarctica than in the high plateau of East Antarctica because of the surface elevation.

The tracks of sea level depressions (at 700 mb level on the continent) indicated in Figure 7A (after Alt and others, 1959, Fig. 4) show that a depression must move at least 1000 km, while ground elevation rises to more than 2500 m above sea level, before reaching the region covered by the traverse. The location of the major atmospheric troughs and ridges, and hence the advection of moisture, vary from season to season (Rubin, 1960b, p. 380-386). However, monthly charts of sea level pressure (van Loon, 1961, p. 109-112), 700 mb and 500 mb levels (Alt and others, 1959, Figs. 5-81), show that in general the patterns of circulation can be considered constant throughout the year (Fig. 7B).

The tracks of sea level depressions (Fig. 7A), which are represented on the continent at the 700 mb level and the simplified features at this level, depict the atmospheric circulation, although the anticyclone shown as centered in the interior of East Antarctica does not actually exist at the 700 mb level because the surface is above it. Air masses moving into the continent via the eastern Ross Ice Shelf-Marie Byrd Land sector and the eastern Weddell Sea-Queen Maud Land sector converge in the region of the South Pole and flow out from the continent via Victoria Land. In this pattern of circulation the atmospheric ridge over the Bellingshausen Sea and the topographic features, such as the plateau high north of the Thiel Mountains, and the plateau of East Antarctica, are of paramount importance. In general, the relative location of atmospheric troughs and ridges to topographic highs seems to favor a circulation which is geographically coincident with the direction of change in the rate of mass accumulation. Commenting on aspects of the Antarctic atmospheric circulation for 1958, Alt and others (1959, p. 27) concluded that the advection of cold and warm air takes place mostly in the lower half of the troposphere and that there are three main areas of inflow of warm air: Marie Byrd Land, the eastern Weddell Sea-Queen Maud Land Sector, and the Adelie Coast. They concluded also that there are three areas of outflow (see arrows in Fig. 7B), one of them being Victoria Land.

The circulation at the 500 mb level southwest of the Ross Ice Shelf is of importance considering the surface elevation. In van Loon's charts of the average 500 mb absolute topography at three month intervals (Fig. 8), one can see the coincidence of the circulation with the direction of the general decrease in the rate of accumulation, i.e. from the Marie Byrd Land-Bellingshausen Sea and eastern Weddell Sea-Queen Maud Land sectors, toward the plateau of East Antarctica, and approximately along 130°-160°E to the southern region of the Victoria Land-eastern Wilkes Land sector.

Topographic features

Without accurate data on condensation levels a discussion of specific topographic features cannot clarify the relation between atmospheric circulation and mass accumulation. However, some discussion on this point may validate the preceding arguments, primarily in reference to the region covered by the traverse.

With due regard to the paucity of the data, a steady decrease in the rate of mass accumulation is observed north of 88°S (Fig. 3). Air masses moving from the Ross Sea-Weddell Sea sector across the topographic high between the South Pole and the Queen Maud Range, and across this range and the Horlick Mountains (Fig. 1), have to reach an elevation over 3000 m.a.s.l. This could account for the decrease in the rate of mass accumulation north of 88°S. A study of the lifting condensation level of air masses (700 mb) moving on the continent along the tracks corresponding to the sectors of Ross, Amundsen and Weddell seas indicates that this level is between 2700 and 3000 m.a.s.l. (Rubin and Giovinetto, in press).

Boyd (in Crary and others, 1962, p. 2796) determined rates of accumulation in the order of 25 $g.cm^{-2}yr^{-1}$ at locations on the Ross Ice Shelf northeast of the Queen Maud Range. This range rises abruptly 2500 to 4000 m in the path of meridional depressions and in the path of the general clockwise circulation on the ice shelf. The possible effect of the Queen Maud Range on the mass import from the northeast to the west and southwest is suggested by the pronounced reduction in the rate of accumulation from the Ross Ice Shelf to Stations 108 to 110. In turn, it indicates a possible east-west variation in the rate of accumulation on the plateau at 86°S similar to that determined at 78°S (p. 17).

The steep surface slope of the section at longitude 140°E (Fig. 5) is another example of the effects on the mass accumulation of a sharp rise in the surface elevation near the coast. In this particular case the rise is in the path of meridional and circular depressions and the rate of accumulation determined by Lorius depicts its effects on the inflowing warm air.

Clearly the water vapor import by those air masses cannot be significant south of latitude 70°S, where the surface elevation is greater than 2500 m. Figure 5 shows the probable decrease of the rate of net mass accumulation between 71° and 78°S along 140°E.

A study of the condensation level of air masses converging from the Indian Ocean to the region covered by the traverse is in preparation.

SUMMARY AND CONCLUSIONS

The route of the McMurdo-South Pole Traverse can be generally located at 140°E, between 78° and 90°S. Consideration of the topographic and meteorological environs along the route of the traverse indicate similar characteristics in the processes affecting the strata at the surface in the whole region, such as absence of summer melt phenomena, intense sublimation activity (both phases) caused by large annual and periodic air temperature variations, constant drifting snow, etc.

The interpretation of snow stratigraphy was based on criteria adopted after examination of sections at Stations 100 and South Pole, where snow accumulation had been measured at stakes. The results of the stratigraphic studies indicate that the rate of mass accumulation decreases from 7 $g.cm^{-2}yr^{-1}$ at the South Pole to 2 $g.cm^{-2}yr^{-1}$ at Station 100. These figures are in agreement with the range of mass accumulation measured at stake networks during two years at Station 100 and three years at the South Pole.

The study of the variations of annual values of snow accumulation at each stake in those networks shows the local areal variability to be approximately 55% at 90°S and 120% at 78°S. Assuming that the relation between the local areal variability and the temporal variability determined for the South Pole in a current study can be extended toward the north to 78°S, the temporal variability of mass accumulation along 140°E should be between 15% and 55%.

The general rate of mass accumulation indicated along the route of the traverse is approximately one-half of that reported by Lister for the same region with an opposite south-north trend. The difference between the results of the two studies are within the error of interpretation, although to maintain this relationship at 78°-79°S, it is necessary to consider the east-west regional variability of the rate of mass accumulation determined along 78°S, in particular across the trough between Stations 72 and 100. The difference in the south to north trend between both sets of data remains unexplained, and is considered significant because of the permanent sign of the differences, independently of the relative east-west location, of the corresponding stations. The local areal variability and the annual temporal variability do not substantially affect this comparison.

The rate of accumulation determined between 78° and 90°S is arbitrarily continued northward to coincide with the results determined by other investigators between 71°S and the coast. The accumulation profile thus determined for longitude 140°E is used together with data from other sources to complete a chart of net accumulation for Antarctica.

The pattern of the lines joining locations of equal rates of accumulation are related to the relative position of atmospheric troughs and ridges at the 700 and 500 mb levels, and to the trajectories of cyclonic storms and surface elevation. The examination of the atmospheric circulation and topographic features seems to explain (pending a study of the condensation level of the air masses) the decrease in the rate of mass accumulation from the South Pole to Station 100.

In general it is believed that the pronounced decrease in the rate of mass accumulation north of 88° S is caused by the shield effect of the topographic highs in the path of air masses converging from the Ross Sea-Weddell Sea sector to the region covered by the traverse. The water vapor transport southward of 70° S by the air masses converging from Adelie Coast to the region covered by the traverse is hampered because of the steep slope and elevation of the ice sheet between Adelie Coast and 70° S.

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REFERENCES CITED

Alt, J., Astapenko, P. and Ropar, N. J., 1959, Some aspects of the Antarctic circulation in 1958: National Academy of Sciences, IGY General Report Series, No. 4, 27 p.

Anderson, V. H., 1960, A technique for photographing snow-pit stratigraphy: Journal of Geophysical Research, vol. 65, no. 3, p. 1080-1082.

Ball, F. K., 1960, Winds on the ice slopes of Antarctica: p. 9-16 <u>in</u> Antarctic Meteorology, Pergamon Press, New York, 483 p.

Benson, C. S., 1959, Physical investigations on the snow and firn of northwest Greenland 1952, 1953, and 1954: Snow Ice and Permafrost Research Establishment, U. S. Army Corps of Engineers, Research Report 26, 62 p.

Bogoslovsky, V. N., 1958, The temperature conditions (regime) and movement of the Antarctic glacial shield, Symposium of Chamonix: International Association of Scientific Hydrology, pub. no. 47, p. 287-305.

Cameron, R. L. and Goldthwait, R. P., 1961, The US-IGY contribution to Antarctic glaciology, Symposium on Antarctic Glaciology: International Association of Scientific Hydrology, pub. no. 55, p. 7-13.

Crary, A. P. and Robinson, E. S., 1962, Oversnow traverse from McMurdo to the South Pole: Science, vol. 135, no. 3500, p. 291-295.

Crary, A. P., Robinson, E. S., Bennett, H. F., and Boyd, W. W., 1962, Glaciological regime of the Ross Ice Shelf: Journal of Geophysical Research, vol. 67, no. 7, p. 2791-2807.

Crary, A. P. and Wilson, C. R., 1961, Formation of "blue" glacier ice by horizontal compressive forces: Journal of Glaciology, vol. 3, no. 30, p. 1045-1050.

Den Hartog, S. L., 1959, Snow pit work on Little America-Victoria Land Traverse 1958-59: The Ohio State University Research Foundation, Report 825-2, Part II, p. 1-107.

Dolgushin, L. D., 1961, Zones of snow accumulation in eastern Antarctica, Symposium on Antarctic Glaciology: International Association of Scientific Hydrology, pub. no. 55, p. 63-70.

Giovinetto, M. B., 1960a, Glaciology report for 1958, South Pole Station: The Ohio State University Research Foundation, Report 825-2, Part IV, 104 p.

Giovinetto, M. B., 1960b, Accumulation in Antarctica (35°W to 100°W): Memorandum, Project 968, Institute of Polar Studies, The Ohio State University, 3 p.

Giovinetto, M. B., 1960c, Glaciological studies at the South Pole Station (abstract), Simposio Antarctico Argentino, Buenos Aires, November 1959: Union Geodesique et Geophysique Internationale Monographie No. 5, p. 64.

Giovinetto, M. B., 1961, Mass accumulation in West Antarctica: American Geophysical Union, Transactions, vol. 42, no. 3, p. 386-389.

Giovinetto, M. B., (in preparation), Variability of snow deposition at the South Pole: Geophysical and Polar Research Center, University of Wisconsin, Madison.

Gow, A. J., 1961, Drill-hole measurements and snow studies at Byrd Station, Antarctica: Cold Regions Research and Engineering Laboratories, U. S. Army Corps of Engineers, Technical Report 78, 12 p.

Hanson, K. J., 1961, Some aspects of the thermal energy exchange on the south polar snow field and arctic ice pack: Monthly Weather Review, vol. 89, p. 173-177.

Kotliakov, V. M., 1961a, Snow cover in the Antarctic and its role in modern glaciation on the continent, Glaciology Section of the IGY Program, No. 7: The Academy of Sciences of the USSR, Moscow, 246 p.

Kotliakov, V. M., 1961b, O priznakakh sezonnykh otlozhenii snega v tsentral'nykh raionakh Antarkntidy: Biulleten' Sovetskoi Antarkticheskoi Ekspeditsii, no. 26, Morskoi Transport, Leningrad, 52 p.

Kotliakov, V. M., 1961c, The intensity of nourishment of the Antarctic Ice Sheet, Symposium on Antarctic Glaciology: International Association of Scientific Hydrology, pub. no. 55, p. 100-110.

Lamb, H. H. (1959) in Lister, H., 1959, Geophysical investigation of the Commonwealth Trans-Antarctic Expedition, 1; The climate and ice balance: The Geographical Journal, vol. CXXV, parts 3-4, p. 354-356.

Lister, H., 1956, British North Greenland Expedition 1952-54; Scientific Results VI, Glacier regime in northeast Greenland: The Geographical Journal, vol. CXXII, p. 230-237.

Lister, H., 1959, Geophysical investigations of the Commonwealth Trans-Antarctic Expedition, 1; The climate and ice balance: The Geographical Journal, vol. CXXV, parts 3-4, p. 343-351.

Lister, H., 1960, Glaciology 1. Solid precipitation and drift snow: Trans-Antarctic Expedition 1955-1958, Scientific Reports 5, London, 51 p.

Loewe, F., 1956, Contributions to the glaciology of the Antarctic: Journal of Glaciology, vol. 2, no. 19, p. 657-665.

Lorius, C., 1962, Contribution to the knowledge of the Antarctic Ice Sheet; A synthesis of glaciological measurements in Terre Adélie: Journal of Glaciology, vol. 4, no. 31, p. 79-92.

Mellor, M., 1958, Australian glaciological contributions in Antarctica - Preliminary report: Journal of Glaciology, vol. 3, no. 24, p. 279-285.

Mellor, M., 1959, Mass balance studies in Antarctica: Journal of Glaciology, vol. 3, no. 26, p. 522-533.

Mellor, M., 1960, Temperature gradients in the Antarctic Ice Sheet: Journal of Glaciology, vol. 3, no. 28, p. 773-782.

Pirrit, J. and Doumani, G. A., 1960, Glaciology, Byrd Station and Marie Byrd Land Traverse 1959-60: The Ohio State University Research Foundation, Report 968-2, 177 p.

Rubin, M. J., 1960a, Discussion, Session 1: p. 69-71 in Antarctic Meteorology, Pergamon Press, New York, 483 p.

Rubin, M. J., 1960b, Advection across the Antarctic Boundary: p. 378-393 in Antarctic Meteorology, Pergamon Press, New York, 483 p.

Rubin, M. J., 1961, Atmospheric advection and the Antarctic mass and heat budge: p. 318 in Abstracts of the Tenth Pacific Science Congress, Honolulu, 487 p.

Rubin, M. J. and Giovinetto, M. B., 1962, Snow accumulation in central West Antarctica as related to atmospheric and topographic factors: Journal of Geophysical Research, vol. 67, p. 5163-5170.

Schytt, V., 1958, Glaciology II; A. Snow studies at Maudheim, B. Snow studies inland, C. The inner structure of the ice shelf at Maudheim as shown by core drilling: Norsk Polarinstitutt, Oslo, 151 p.

Sharp, R. P. and Epstein, S., 1962, Comments on annual rates of accumulation in West Antarctica, Symposium of Obergürgl: International Association of Scientific Hydrology, pub. no. 58, p. 273-285.

Sorge, E., 1935, Glaziologische untersuchungen in Eismitte: Wissenschaftliche Ergebnisse der deutschen Grönland-Expedition Alfred Wegener 1929 und 1930-31, vol. 3, Leipzig, Brockhaus, p. 62-270.

Stuart, A. W. and Heine, A. J., 1961a, Glaciology, Victoria Land Traverse, 1959-60, IGC Antarctic glaciological data field work 1959-60: The Ohio State University Research Foundation, Report 968-1, 93 p.

Stuart, A. W. and Heine, A. J., 1961b, Glaciological work of the 1959-60 U. S. Victoria Land Traverse: Journal of Glaciology, vol. 3, no. 30, p. 997-1002.

van Loon, H., 1961, Charts of average 500 mb absolute topography and sealevel pressure in the Southern Hemisphere in January, April, July, and October: South Africa. Weather Bureau. Southern Hemisphere Analysis Project. Notos. vol. 10, no. 14, Pretoria, p. 105-112.

Vickers, W., 1958, Glaciological report of the airborne traverse unit, 1957-58: The Ohio State University Research Foundation, Report 825-1, Part I, 297 p.

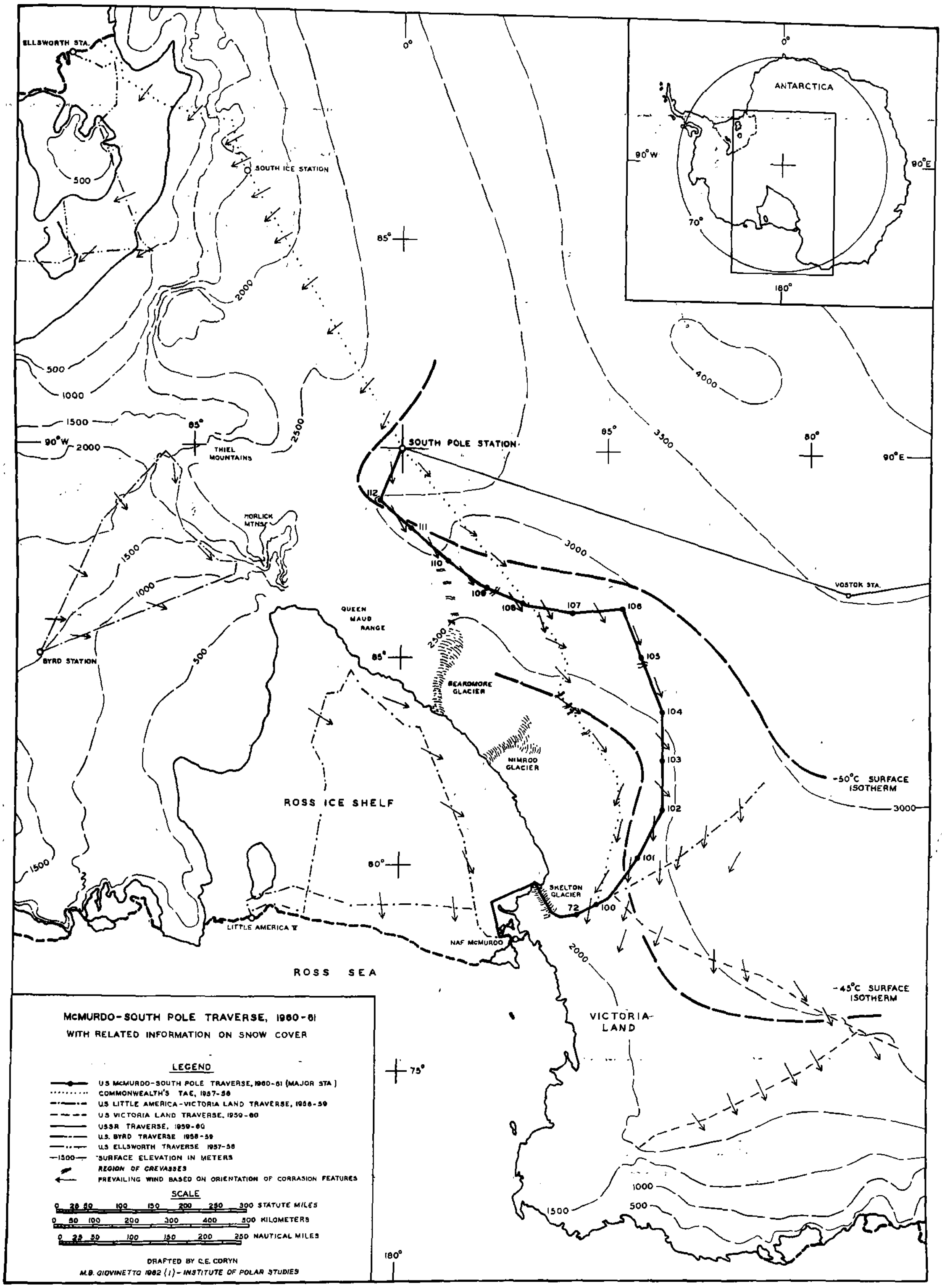


Fig. 1. Index map showing location of the U. S. McMurdo-South Pole Traverse, 1960-61, and other traverses referred to in the text. Also, related information on snow cover for this part of Antarctica is shown.

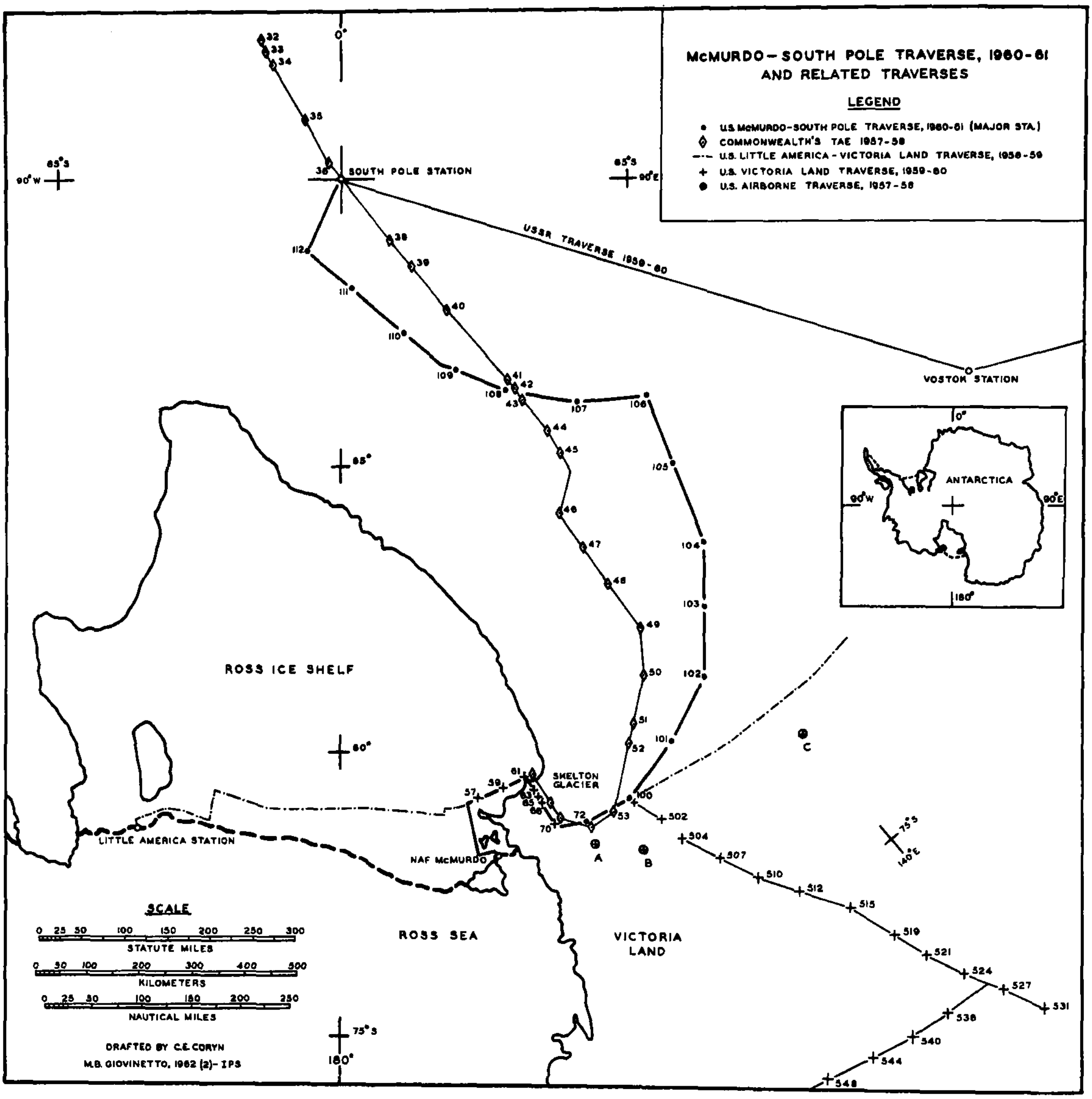


Fig. 2. Index map showing route and stations of McMurdo-South Pole Traverse, 1960-61 and related traverses

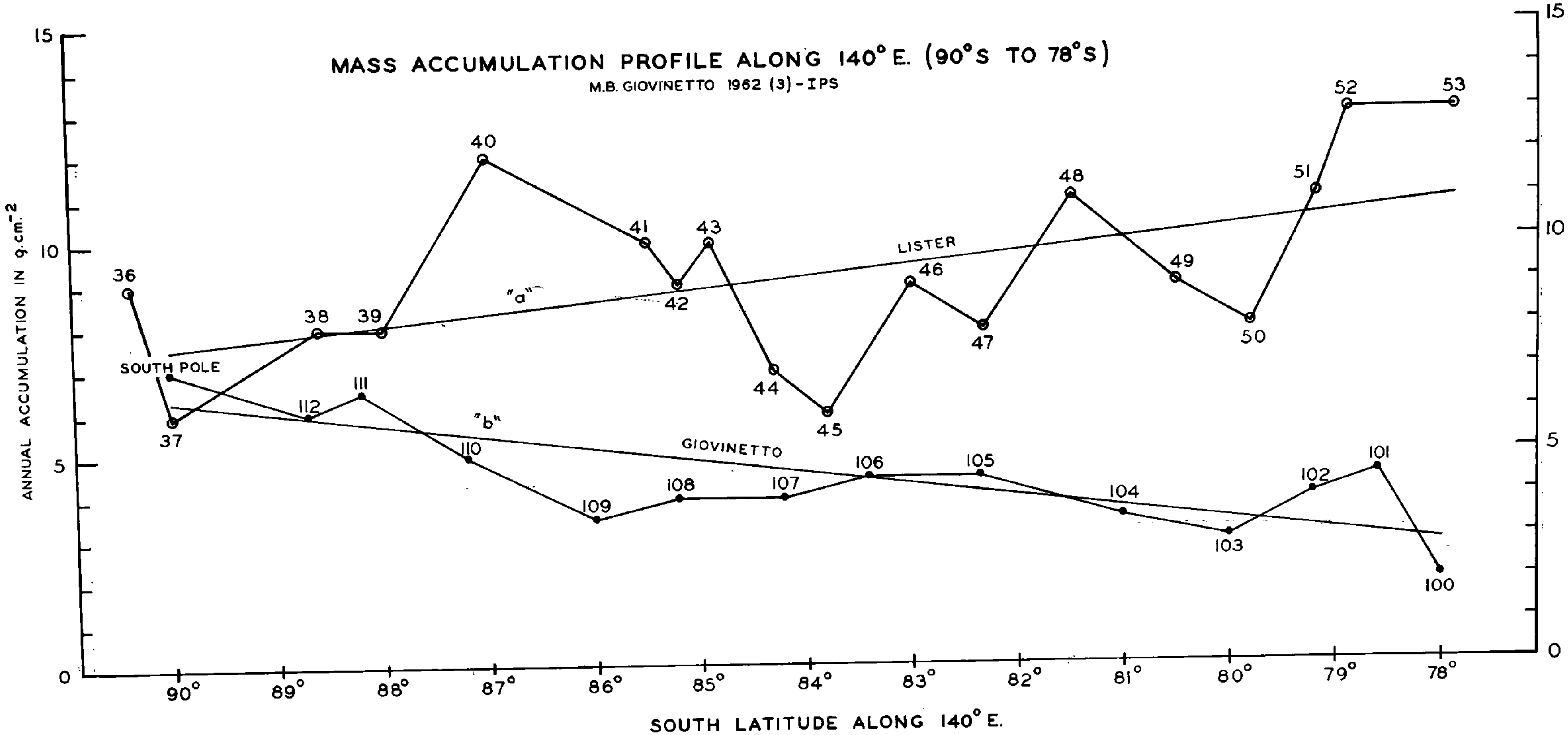


Fig. 3. Mass accumulation profile along longitude 140°E, as determined by Giovinetto and Lister

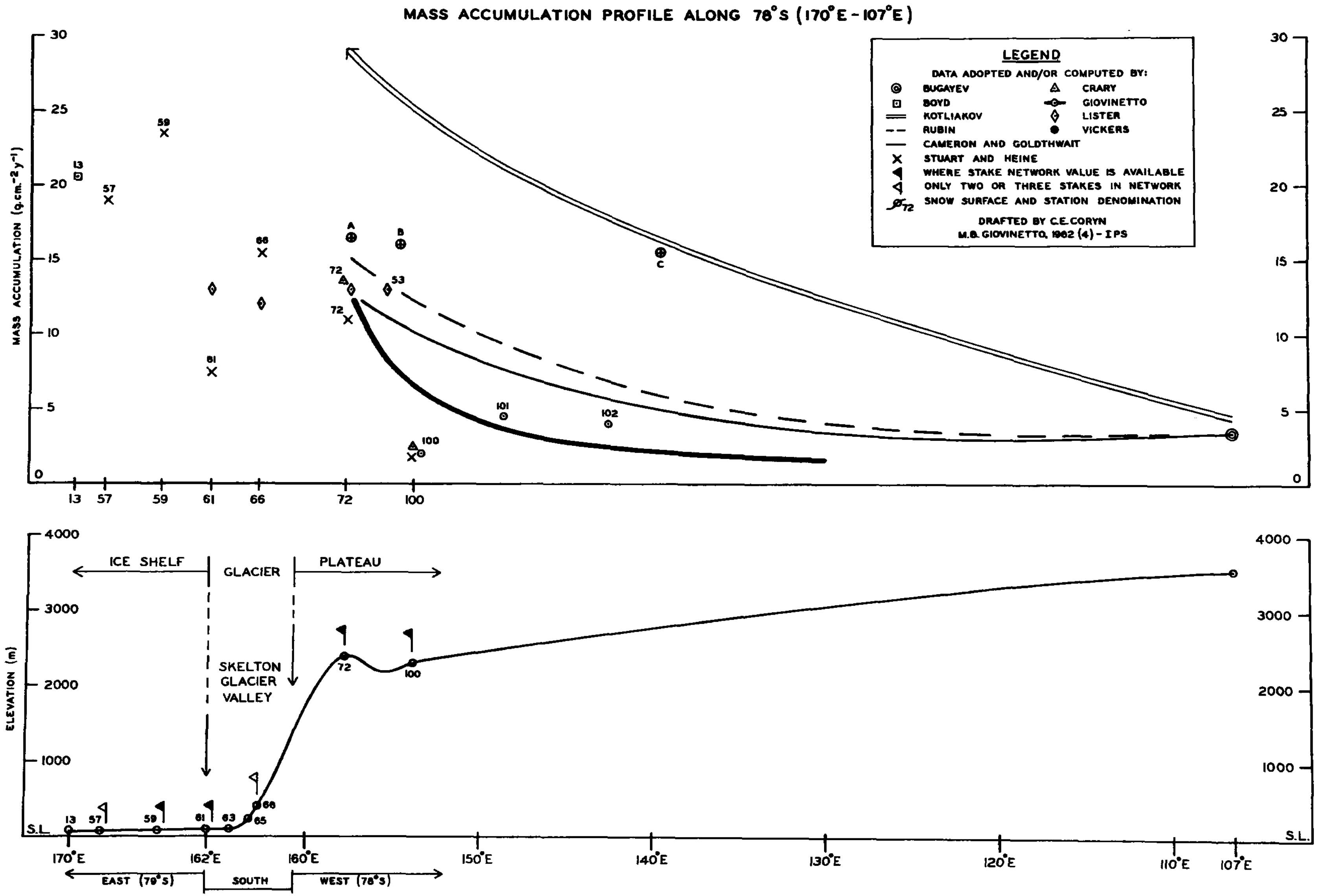


Fig. 4. Mass accumulation profile along latitude 78°S

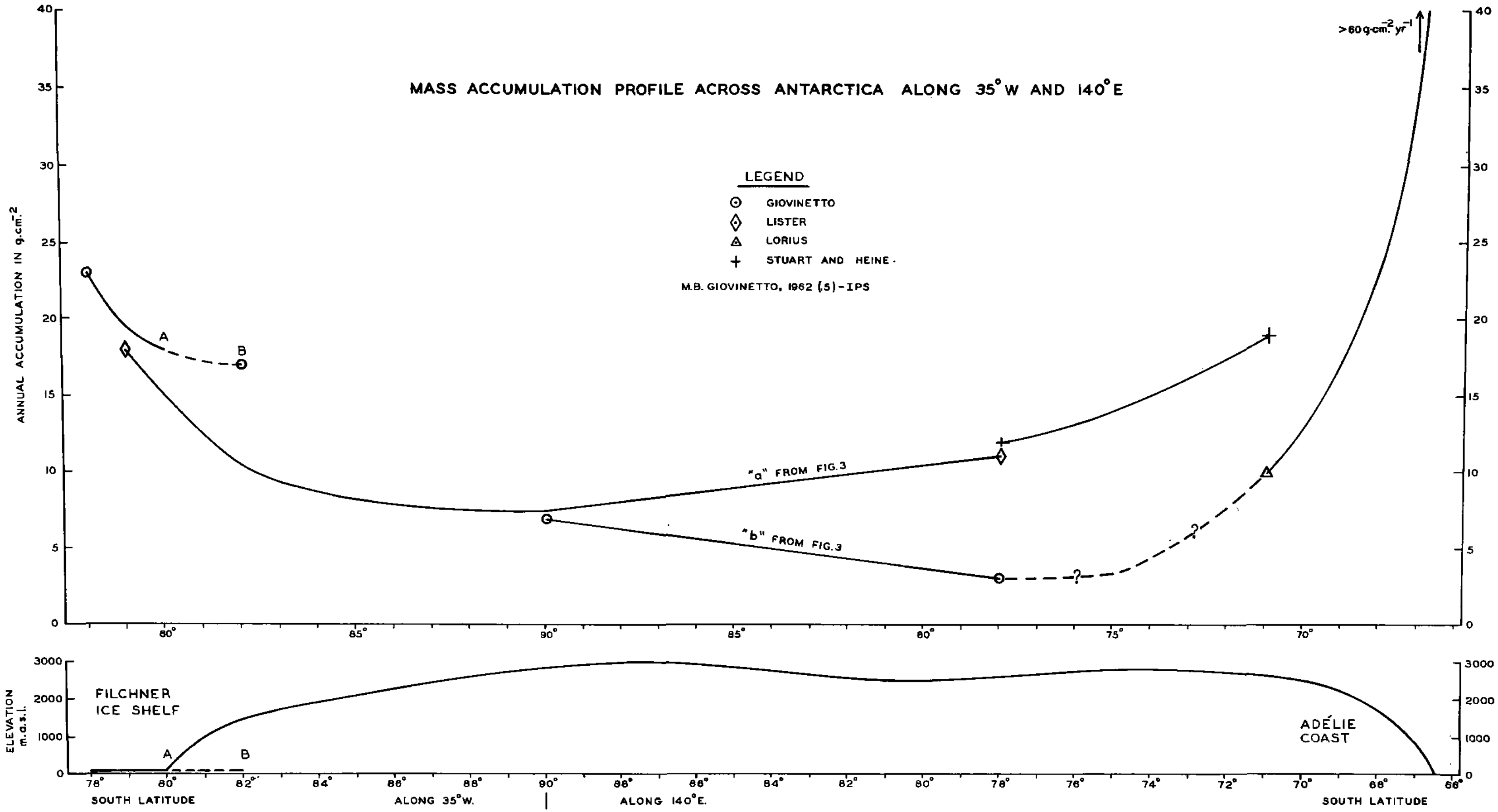


Fig. 5. Mass accumulation profile across Antarctica along longitudes 35°W and 140°E

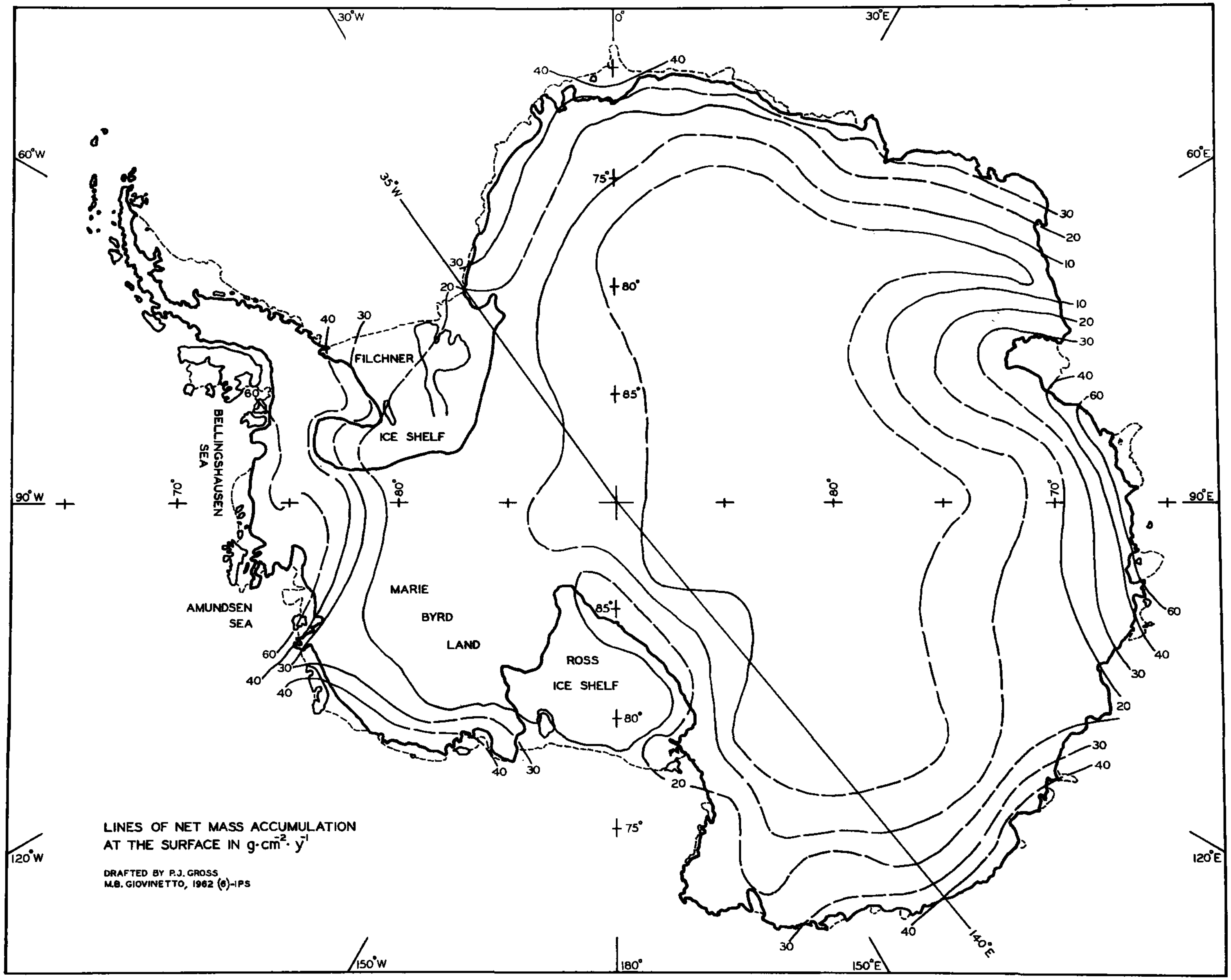


Fig. 6. Contour map of net mass accumulation of Antarctica. Line of profile along longitudes 35°W and 140°E, used in Figure 5

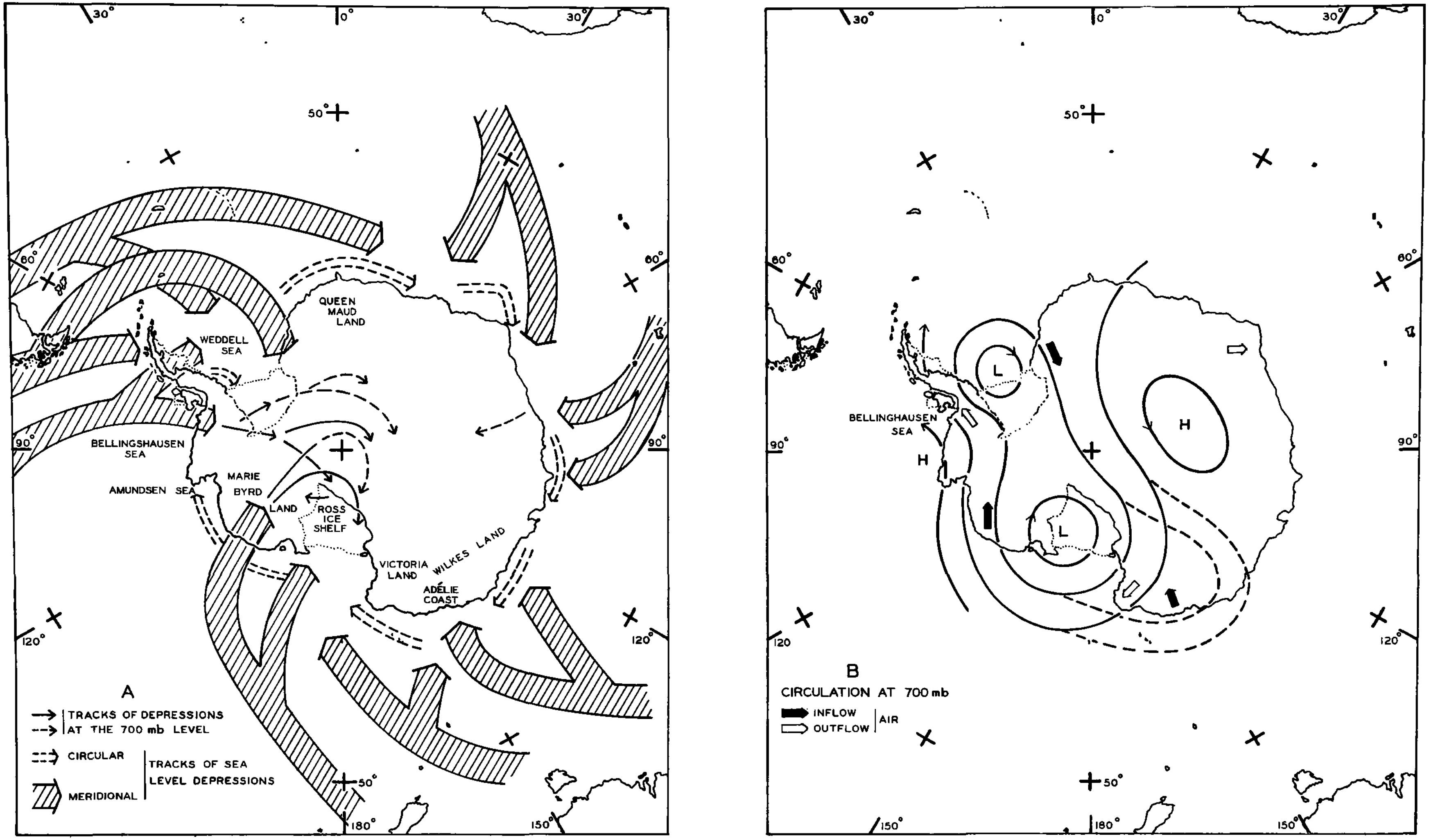


Fig. 7. A - Tracks of sea level depressions, 1958 (after Alt and others, 1959)
B - Chart of circulation at 700 mb level (after Alt and others, 1959)

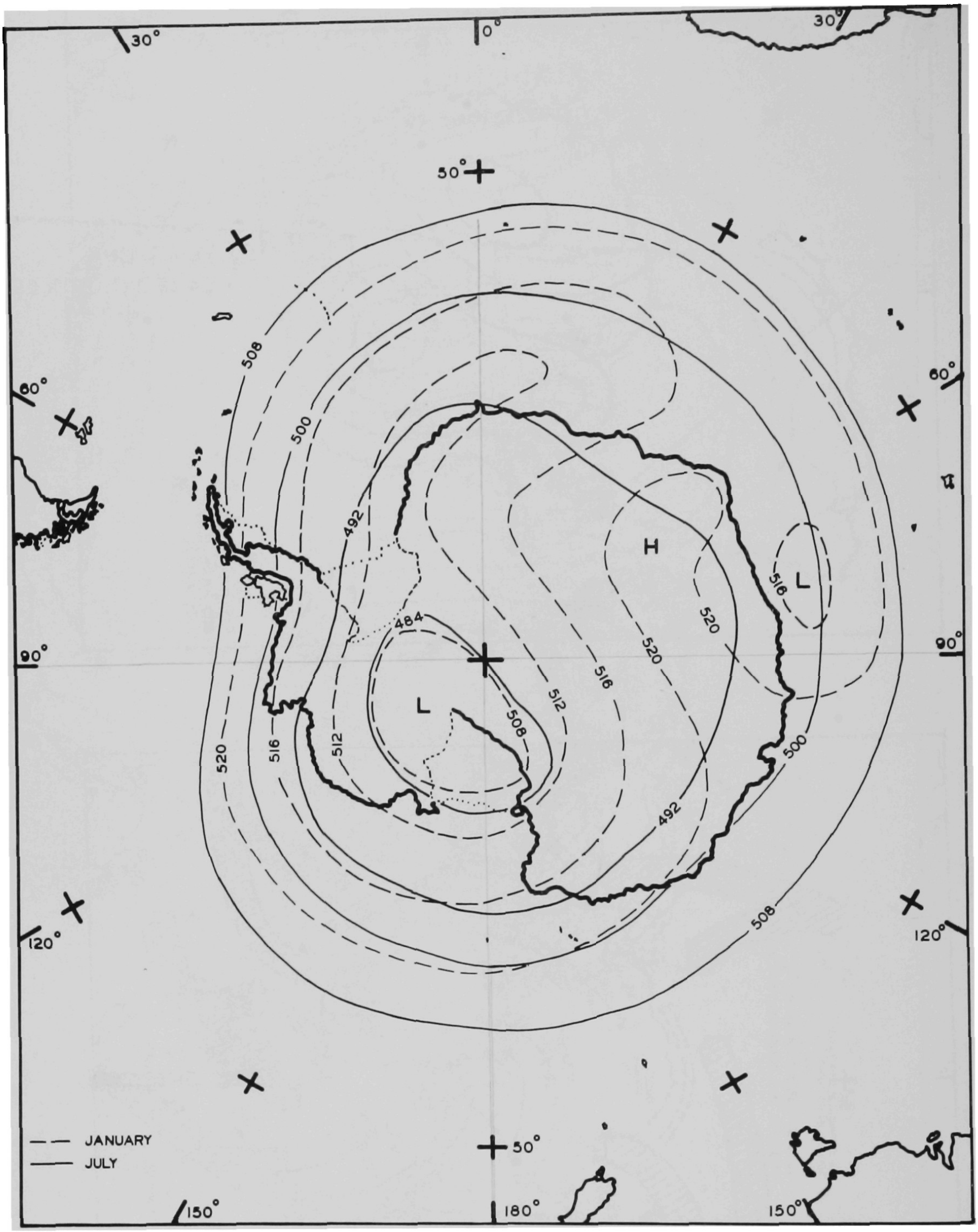


Fig. 8. 500 mb absolute topography (in geopotential dekameters) (after van Loon, 1961)

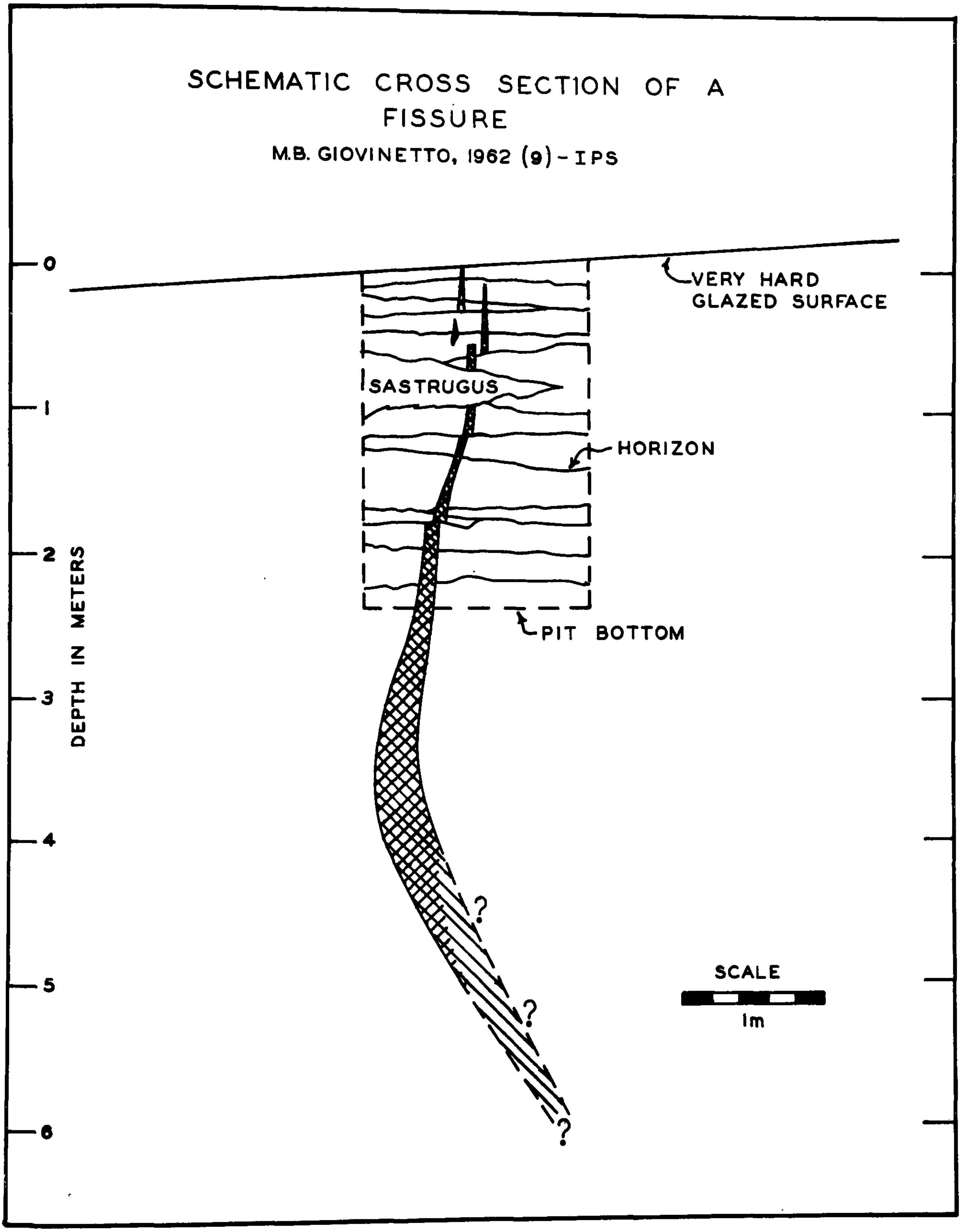


Fig. 9. Schematic cross section of a fissure. Note that upper part is a pit wall.

APPENDIX A

Description of fissures

No preferred orientation of fissures was observed. In pits dug where the fissures joined or where the fissures were found at a depth of 10 cm and below, it generally was observed that their width increased with depth and their sides became more sinuous (see Fig. 9). Besides the interesting problem that the origin of the fissures presents, one of their most puzzling elements is the alternate displacement of segments of the fissure near the surface. These alternations are represented in Figure 9 above a depth of 70 cm; they are less evident at depths of 120 and 180 cm where the shift along a horizon is about one-half its width. There was no indication of steps or any other disturbance in the smooth walls below a depth of 180 cm. The total depth seemed to be 6 m, and it is not known if the plumb used to do the sounding was stopped at the depth by debris or by the closure of the fissure. The maximum width was approximately 30 to 60 cm at a depth of 4 m.

Sublimation crystals increased in size with depth in the fissure; at a depth of approximately 2.5 m they measured 20 mm. If carefully examined, this could be a clue to the length of time of the development of the fissures. The magnitude and increasing width with depth indicates that a thermal process, although a factor in the development, cannot be considered the main cause of these fissures. The rate of surface strain, being larger than the sum of the rates of settling and lateral expansion of the strata close to the surface, seems to merit consideration as a causal element; the small rate of accumulation is favorable to this relationship.

Crevasses

Crevasses were found at approximately 82° 15' S, before reaching Station 105. Lister (1959, p. 347) reported crevasses at several points between 81° 30' S and 83° S. Snow surface and subglacial topography in the region are little known, but it is possible that these crevasses areas are related to the drainage basin of the Nimrod Glacier. Crevasses were found again at 85° 40' S, between Stations 108 and 109. Scott and his party observed crevasses along 160° E from the top of the Beardmore Glacier as far south as 87° S. It may be that the crevasses found between Stations 108 and 109 are related to the drainage basin of the Beardmore Glacier.

Snow stratigraphy

The techniques used to observe snow stratigraphy were those advocated by the Cold Regions Research and Engineering Laboratories (formerly S.I.P.R.E.) with some recommended modifications.

1. All observations were made in a stratigraphic column with a horizontal section not larger than 600 cm^2; this included the site of the stake at Stations 100 and the South Pole. This is the best way to ensure depth correlation between the general description, the grain size, and the hardness and density values of each of the layers where these are very thin and unevenly distributed in depth.

2. Firn photography using transmitted light was made immediately adjacent to the 600 cm^2 column mentioned in 1; methods of photographing the strata in situ have been described by Benson (1959, p. 10-12) and Anderson (1960, p. 1080-1082). In the present study several improvements were made: a diffused light source of constant intensity throughout the depth of the stratigraphic section was used; the depth markers were leveled lines instead of points, thus giving a visual clue to the variation in depth of some horizons and providing a tie-in mark to superimpose successive prints where there are not common stratigraphic details in the overlapping sections. The axis of the camera lenses was held normal to the plane of the stratigraphic section and the exact focal length was maintained for each exposure by means of a cubical aluminum frame which, if necessary, could be held by the man who operated the camera's shutter.

3. The notations of the stratigraphic description, including visual observations of sublimation effects, compaction, etc., were made on a strip of paper, scaled in mm^2 and extended over a board along the total depth of the section studied. Particular stratigraphic notations were made using symbols, speeding up otherwise tedious notations system in full language, and permitting accurate depth location of features. The resultant full-scale stratigraphic notation and the set of photographs obtained as described in 2 were invaluable assets in analyzing the data.

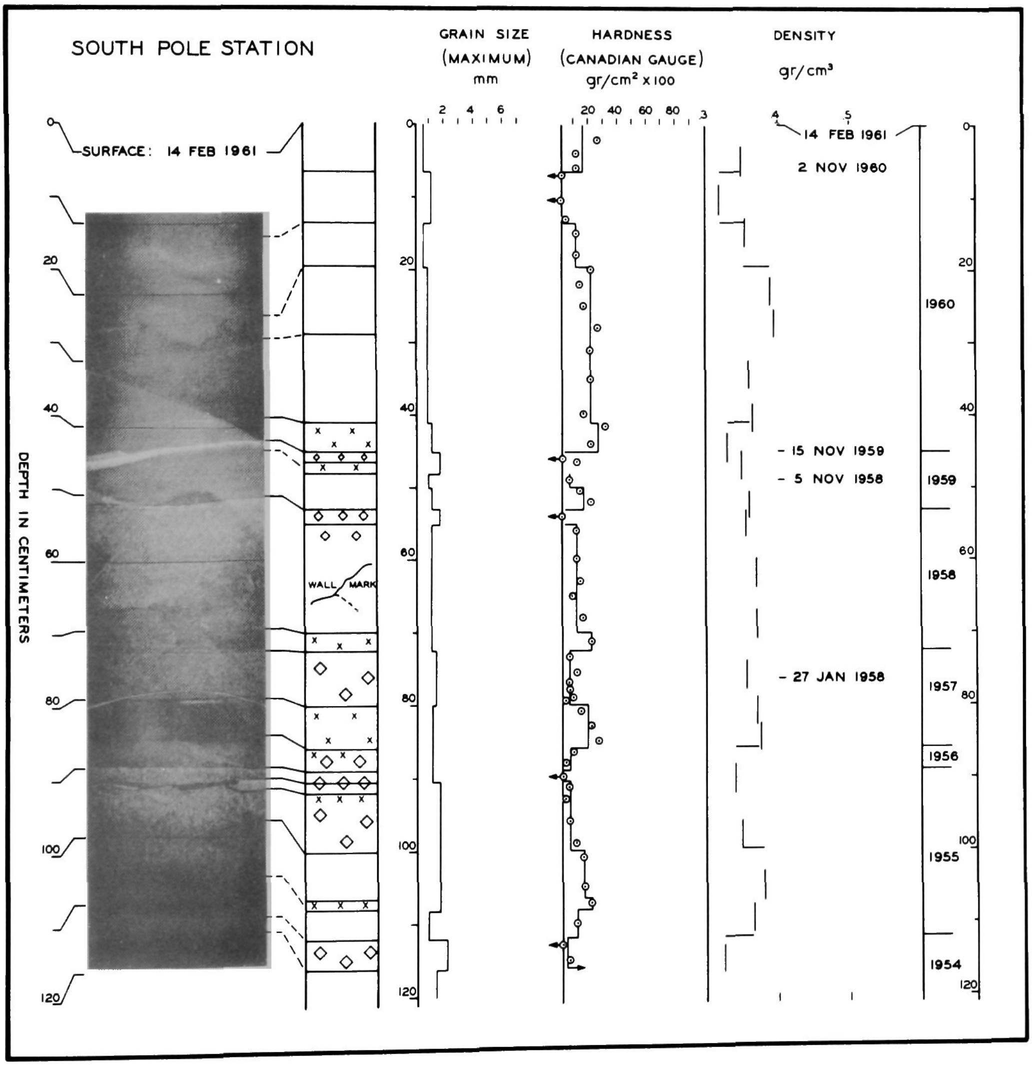
4. Hardness profiles were obtained with both a rammsonde and a Canadian gauge. It is difficult to correlate a rammsonde profile with particular layers because the differences in hardness between consecutive layers are below the useful range of the rammsonde. Furthermore, the absence of ice crusts and infrequent occurrence of very hard layers gave few good keys for correlation of the rammsonde profile with the rest of the observations. Consequently, the rammsonde profile is not shown and the hardness values obtained with the Canadian gauge are used instead; although these values ($g.cm^{-2}$) are not absolute, small differences in hardness are measurable and the readings are accurately placed with the corresponding stratum.

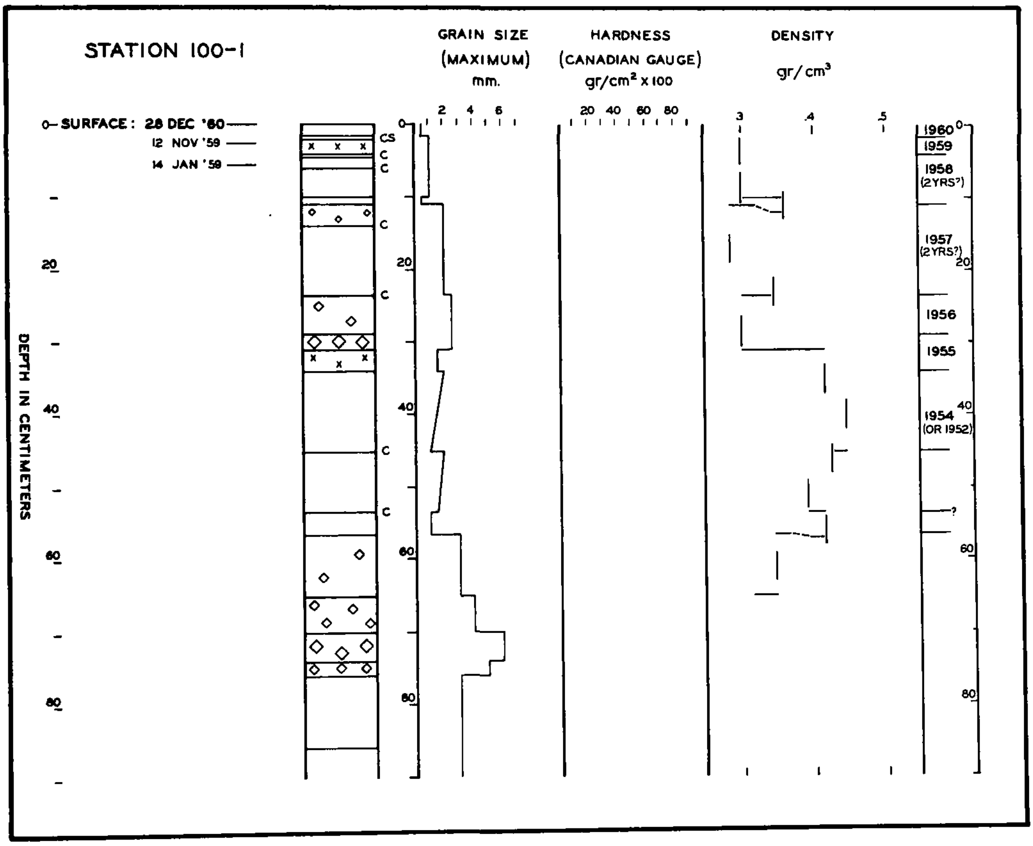
APPENDIX B

PIT STRATIGRAPHY

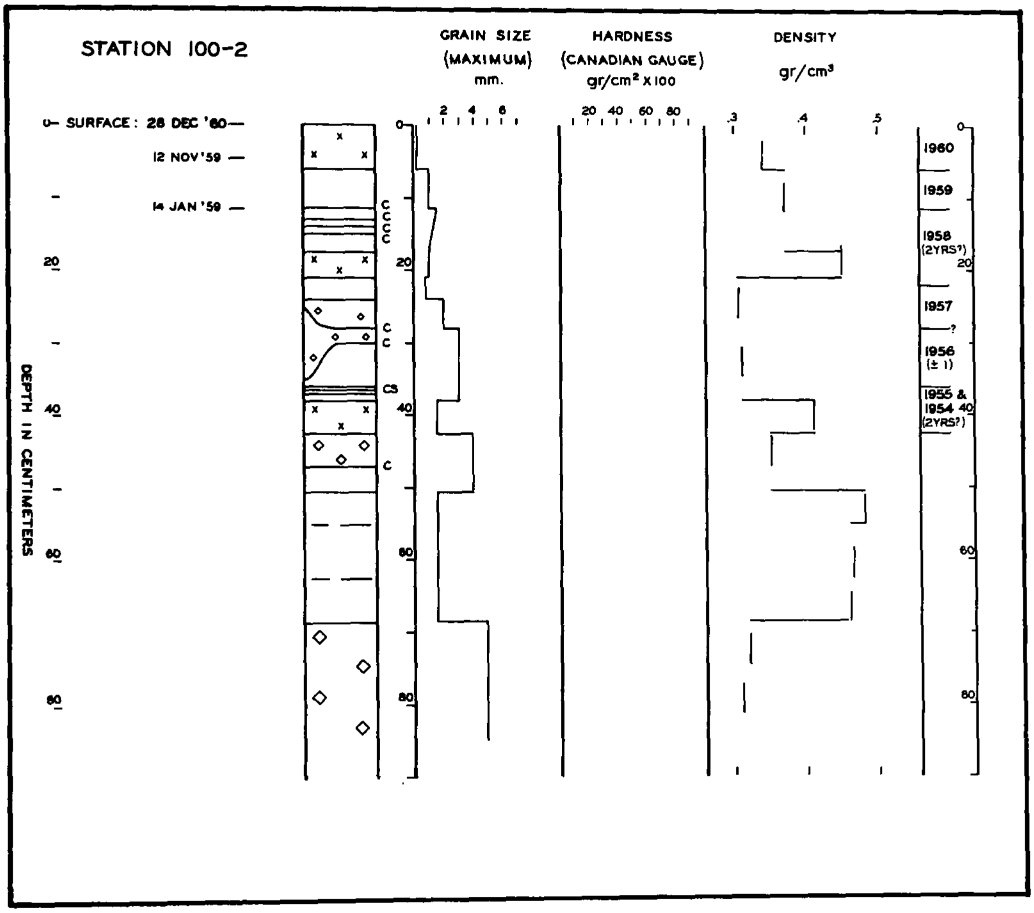
Explanation for Stratigraphy

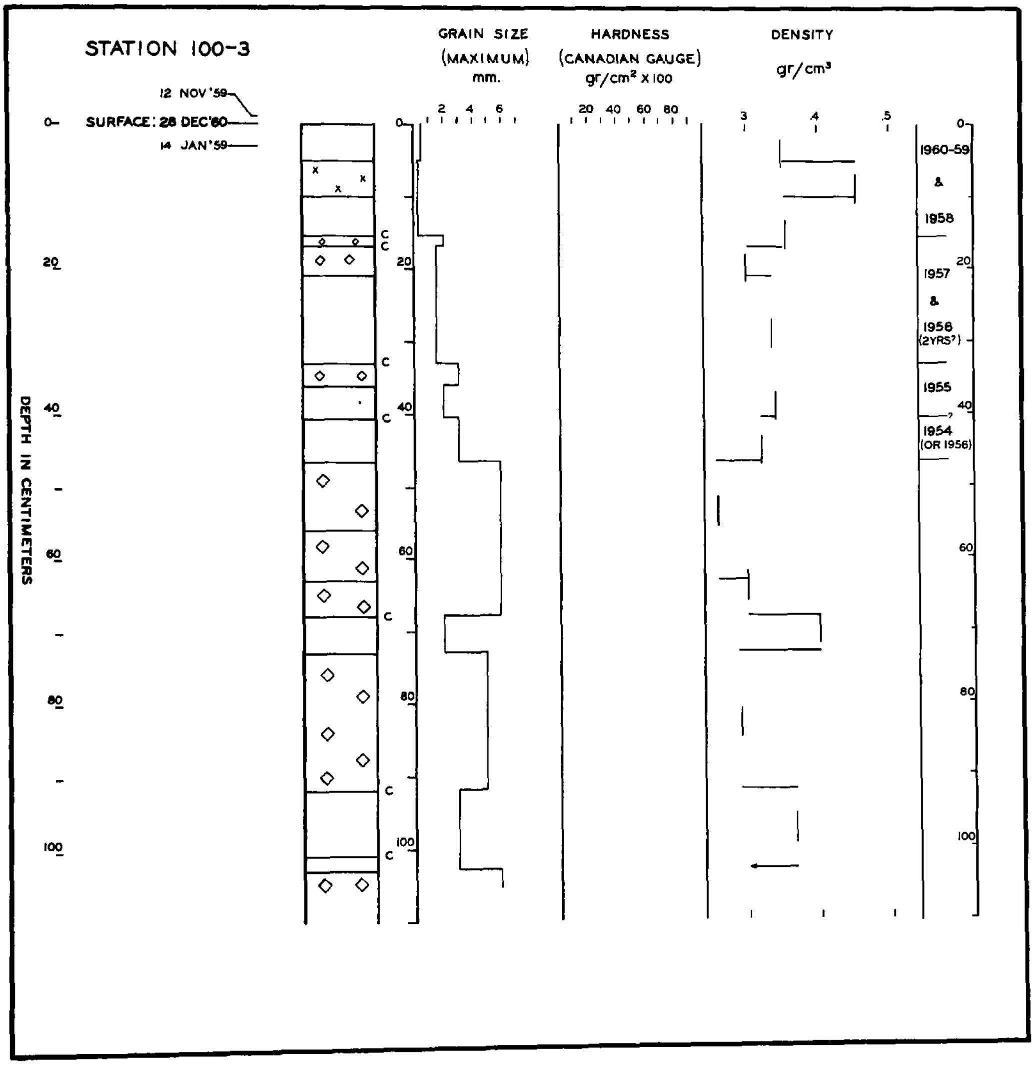
————	:	horizon
————c	:	bonded grains or crust with icy core
XXXXXXXX	:	compacted snow
◇◇◇◇	:	sublimation crystals (or fragments)

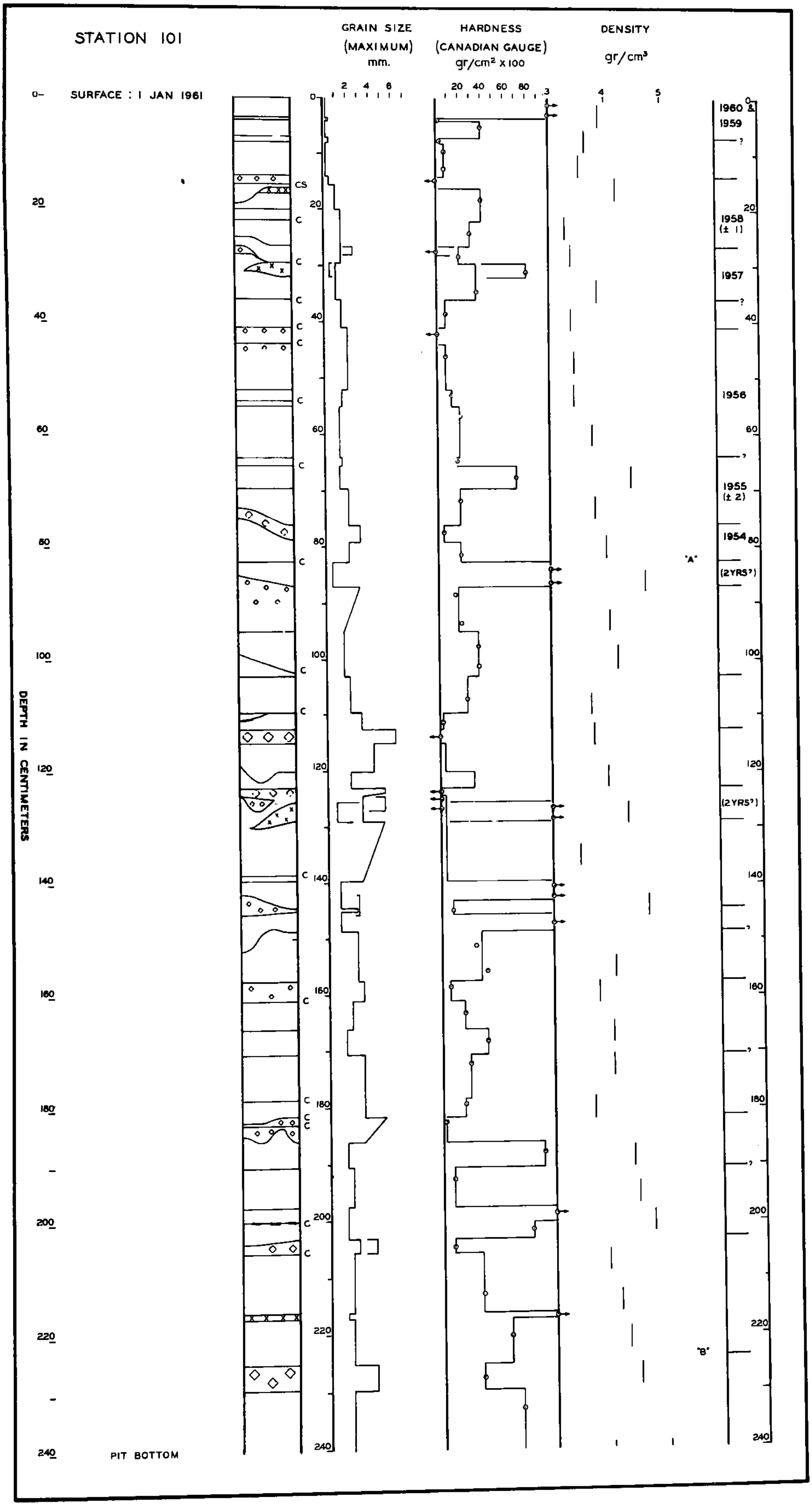

SOUTH POLE STATION
SURFACE: 14 FEB 1961
DEPTH IN CENTIMETERS
0
20
40
60
80
100
120
WALL
MARK
GRAIN SIZE
(MAXIMUM)
mm
2 4 6
HARDNESS
(CANADIAN GAUGE)
gr/cm² x 100
20 40 60 80
DENSITY
gr/cm³
.3
.4
.5
14 FEB 1961
2 NOV 1960
- 15 NOV 1959
- 5 NOV 1958
- 27 JAN 1958
1960
1959
1958
1957
1956
1955
1954

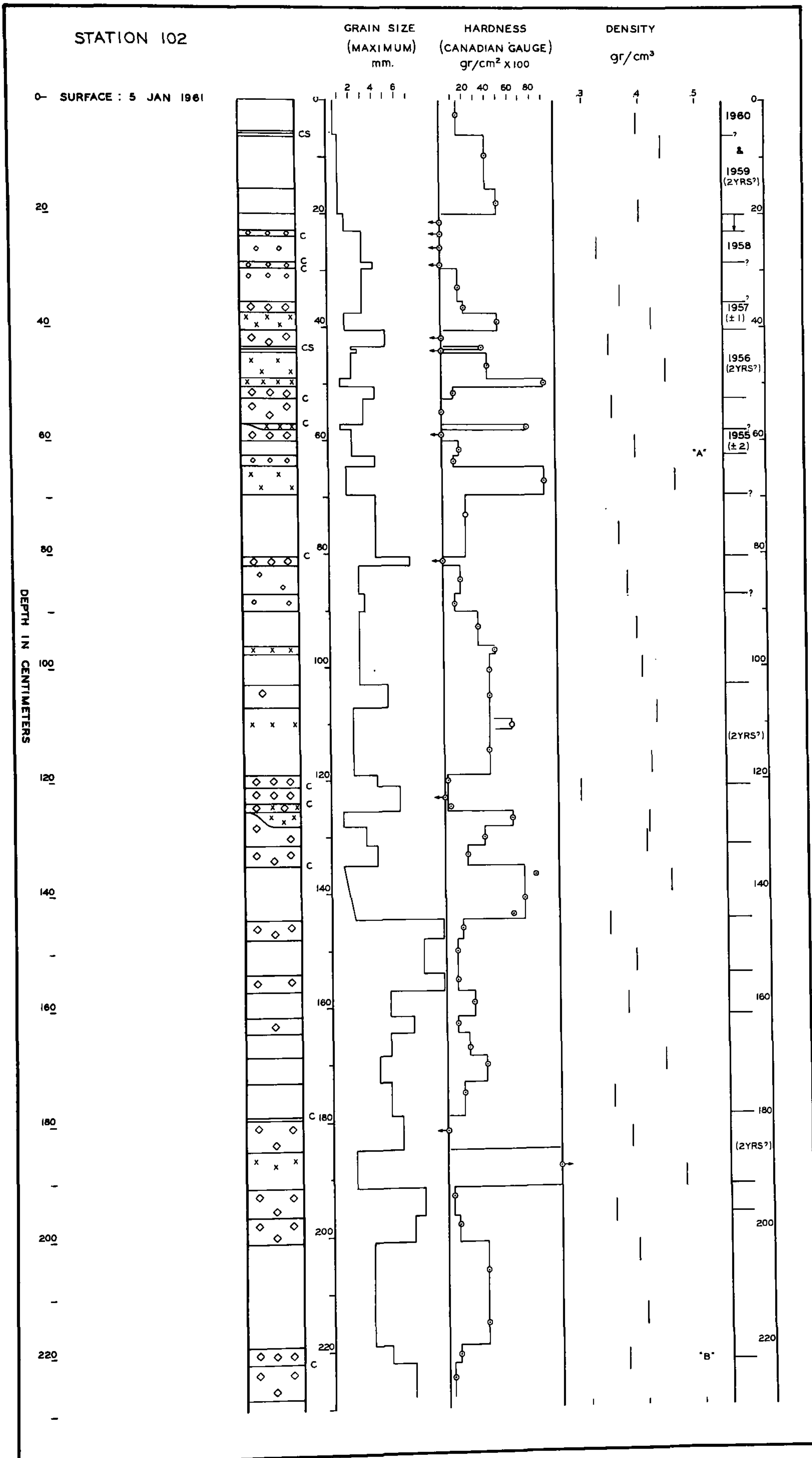


STATION 100-1
GRAIN SIZE (MAXIMUM) mm.
HARDNESS (CANADIAN GAUGE) gr/cm² x 100
DENSITY gr/cm³
0–SURFACE: 28 DEC '60
12 NOV '59
14 JAN '58
DEPTH IN CENTIMETERS
1960
1959
1958 (2YRS?)
1957 (2YRS?)
1956
1955
1954 (OR 1952)

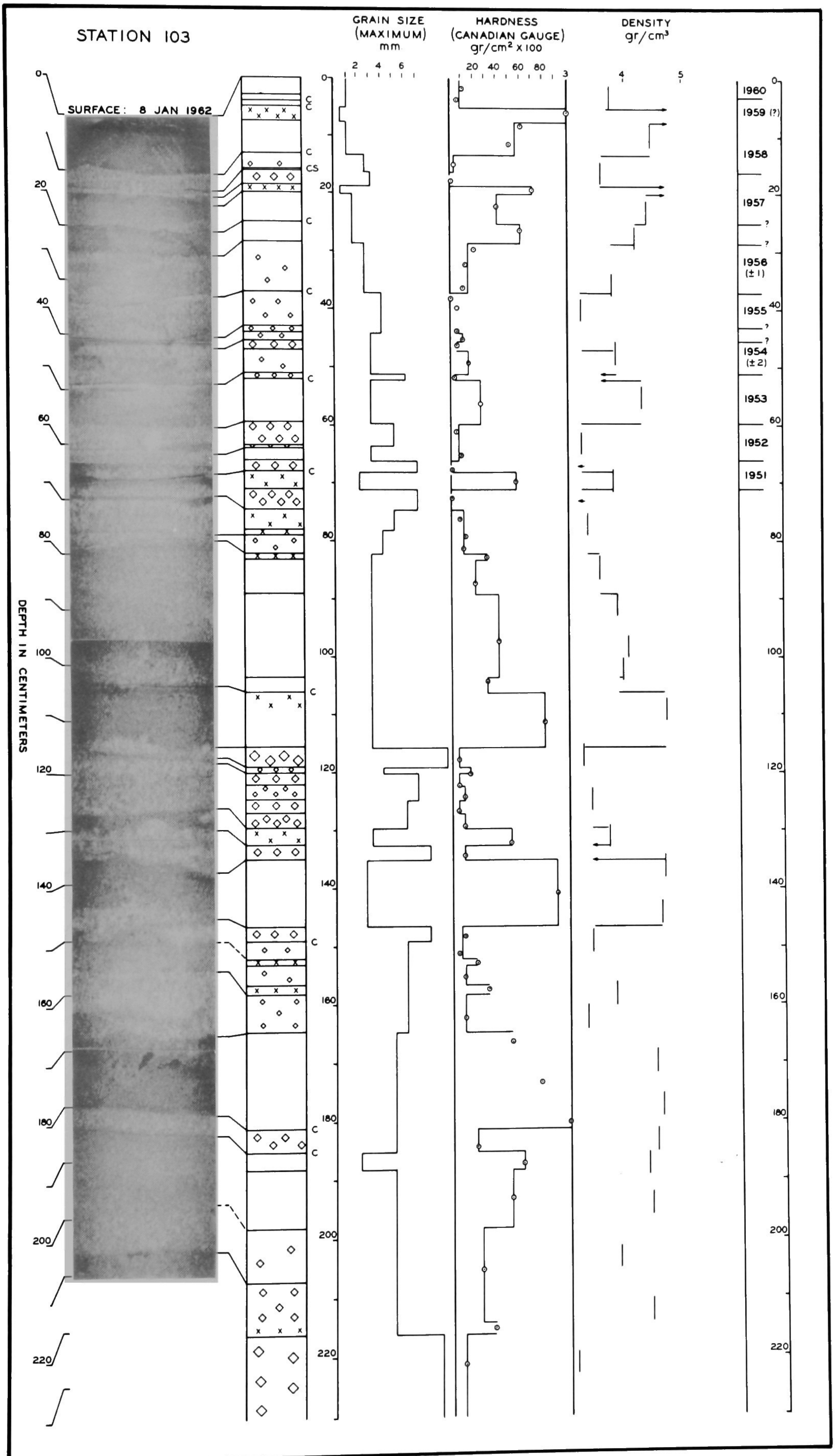

STATION 100-2
GRAIN SIZE (MAXIMUM) mm.
HARDNESS (CANADIAN GAUGE) gr/cm² X 100
DENSITY gr/cm³
0- SURFACE: 28 DEC '60
12 NOV '59
14 JAN '59
DEPTH IN CENTIMETERS
2 4 6
20 40 60 80
.3 .4 .5
1960
1959
1958 (2YRS?)
1957
1956 (± 1)
1955 & 1954 (2YRS?)
C
CS
0
20
40
60
80

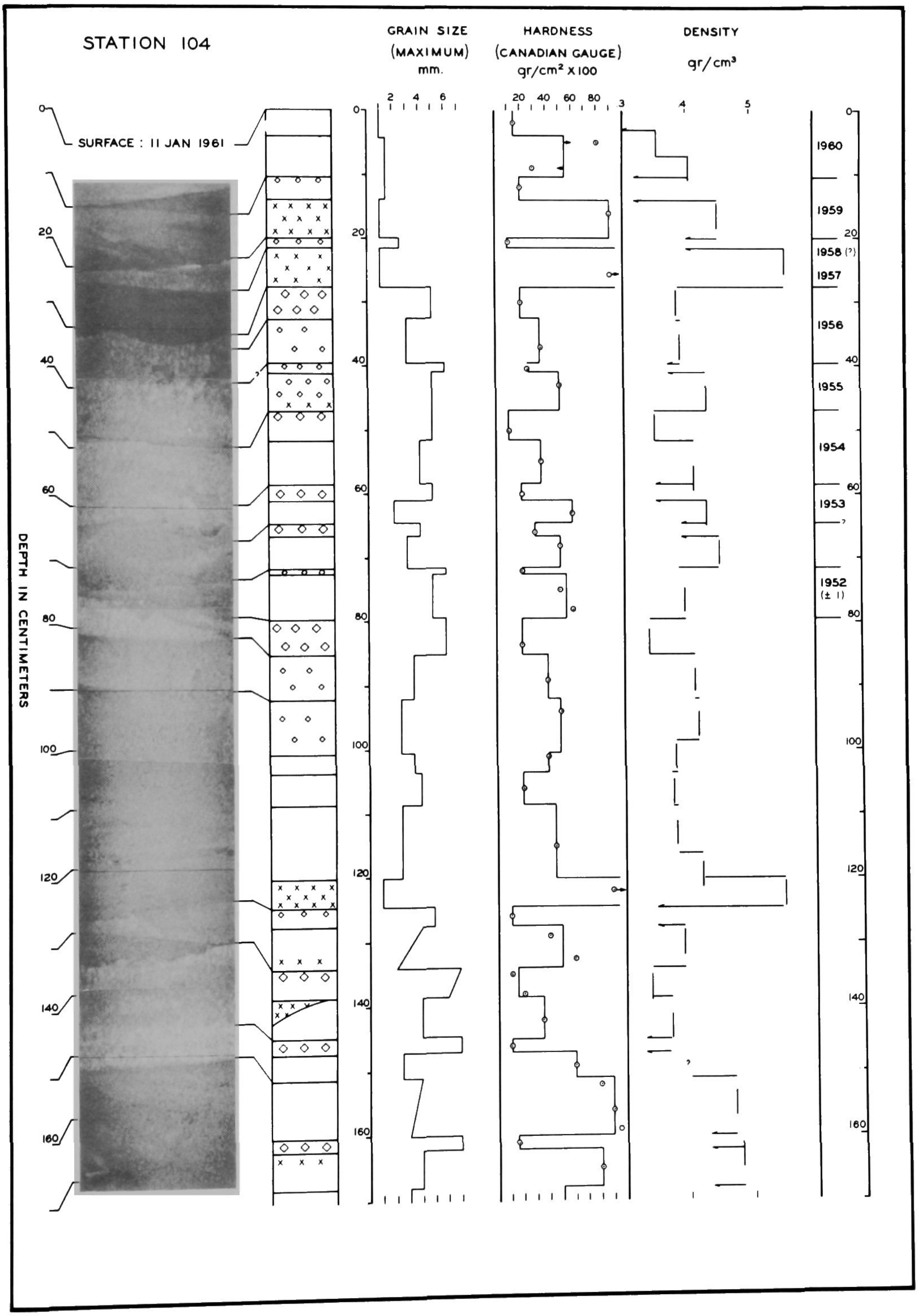

STATION 100-3
GRAIN SIZE (MAXIMUM) mm.
HARDNESS (CANADIAN GAUGE) gr/cm² x 100
DENSITY gr/cm³
12 NOV '59
SURFACE: 28 DEC '60
14 JAN '59
DEPTH IN CENTIMETERS
1960-59 & 1958
1957 & 1956 (2YRS?)
1955
1954 (OR 1956)


STATION 101
SURFACE : 1 JAN 1961
GRAIN SIZE (MAXIMUM) mm.
HARDNESS (CANADIAN GAUGE) gr/cm² x 100
DENSITY gr/cm³
DEPTH IN CENTIMETERS
PIT BOTTOM
1960 & 1959
1958 (± 1)
1957
1956
1955 (± 2)
1954
(2YRS?)
"A"
"B"
CS
C

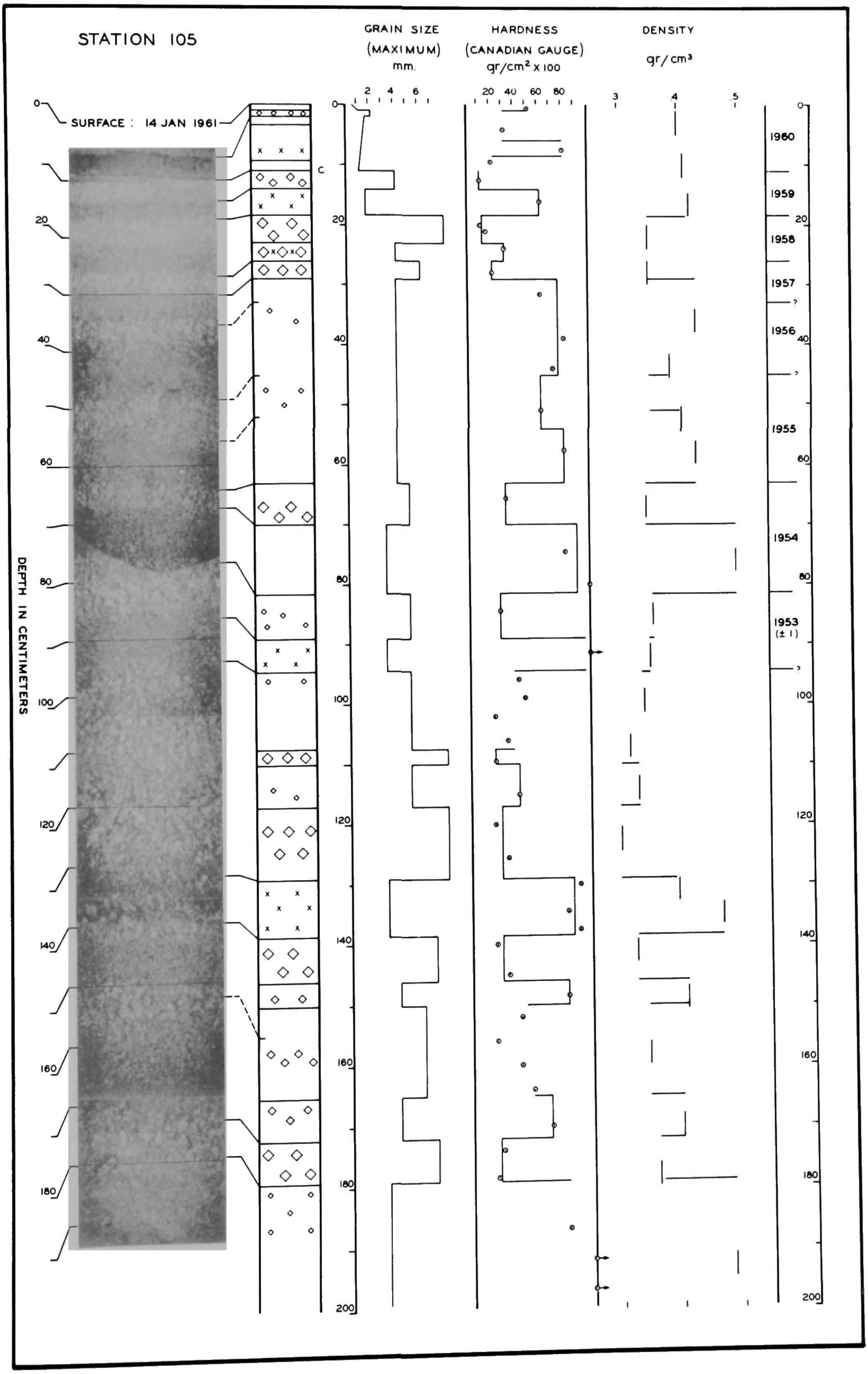


STATION 102
SURFACE : 5 JAN 1961
GRAIN SIZE (MAXIMUM) mm.
HARDNESS (CANADIAN GAUGE) gr/cm² x 100
DENSITY gr/cm³
DEPTH IN CENTIMETERS
CS
C
1960
&
1959 (2YRS?)
1958
1957 (±1)
1956 (2YRS?)
1955 (±2)
(2YRS?)
(2YRS?)
"A"
"B"

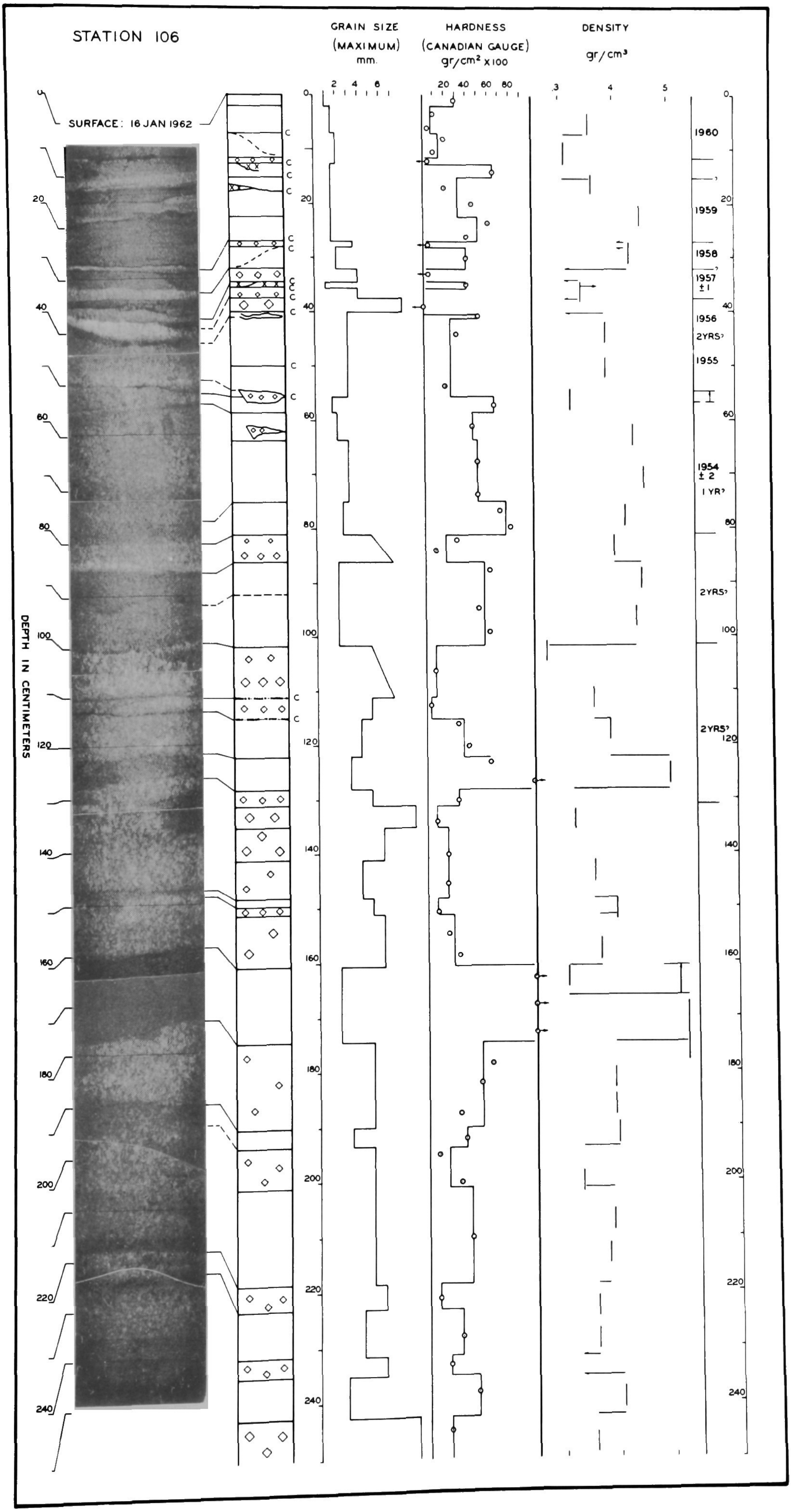

STATION 103
SURFACE: 8 JAN 1962
GRAIN SIZE (MAXIMUM) mm
HARDNESS (CANADIAN GAUGE) gr/cm² x 100
DENSITY gr/cm³
DEPTH IN CENTIMETERS
1960
1959 (?)
1958
1957
1956 (±1)
1955
1954 (±2)
1953
1952
1951



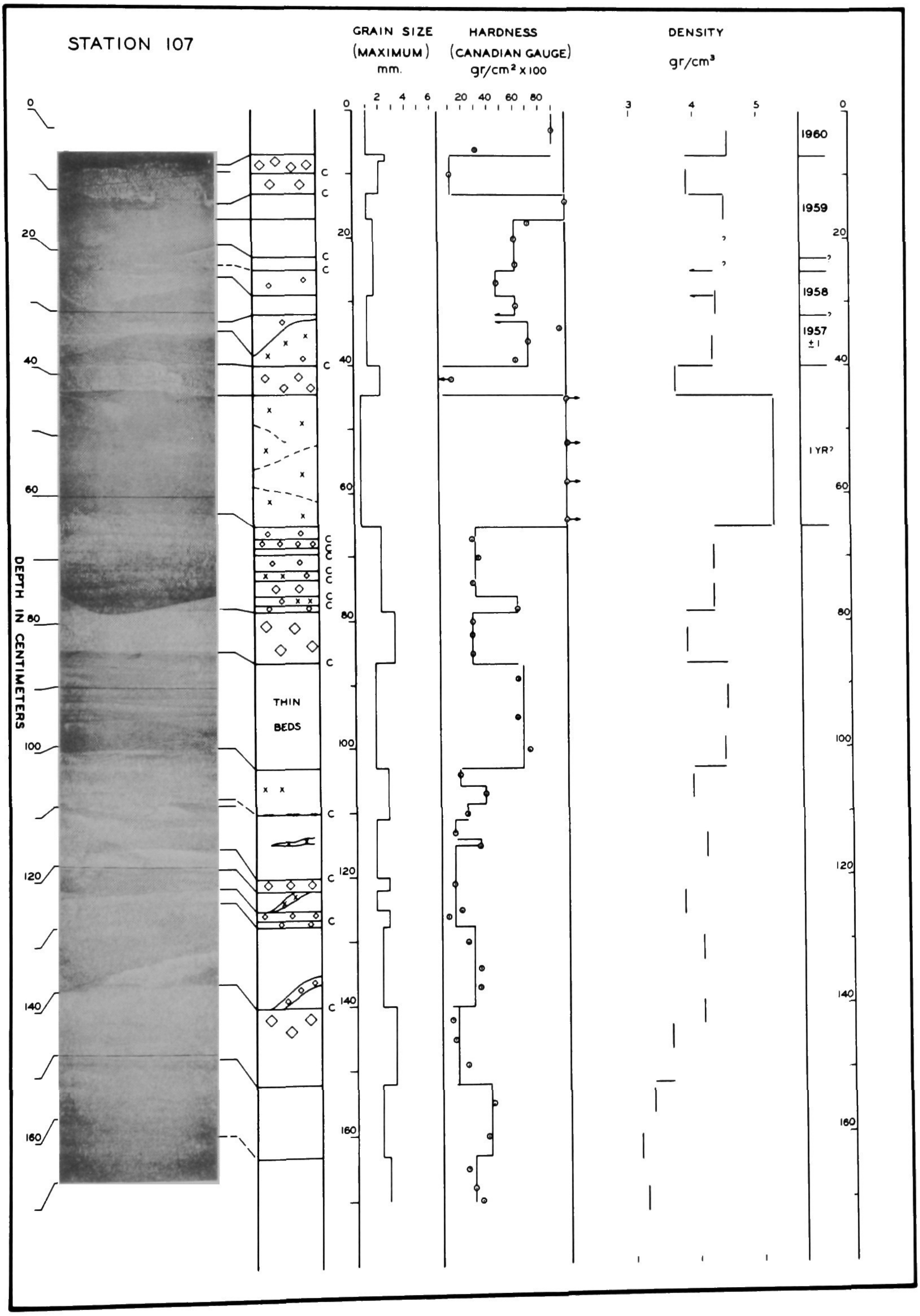
STATION 104
GRAIN SIZE (MAXIMUM) mm.
HARDNESS (CANADIAN GAUGE) gr/cm² x 100
DENSITY gr/cm³
SURFACE : 11 JAN 1961
DEPTH IN CENTIMETERS
1960
1959
1958 (?)
1957
1956
1955
1954
1953
1952 (± 1)

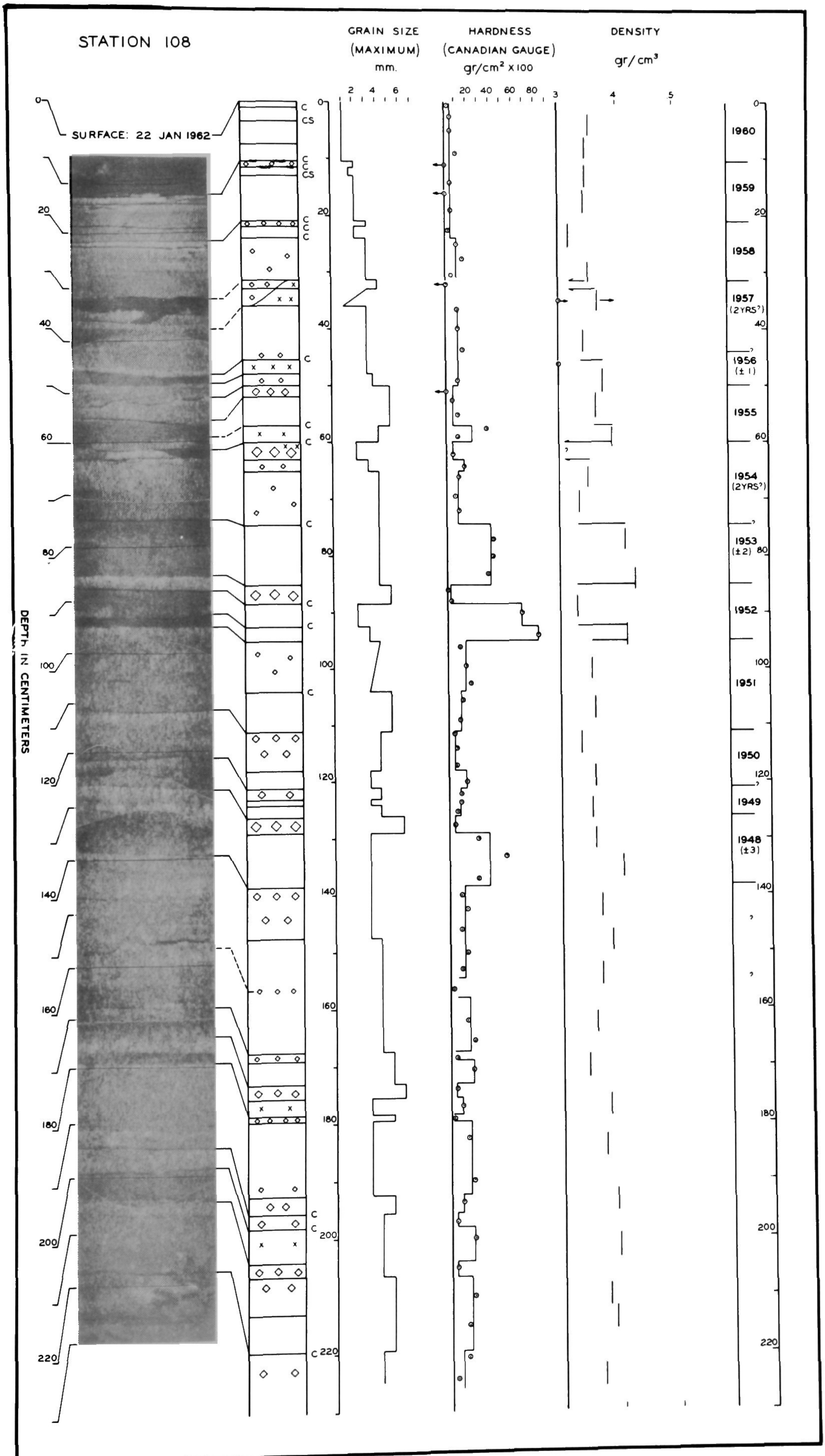


STATION 105
SURFACE : 14 JAN 1961
DEPTH IN CENTIMETERS
GRAIN SIZE (MAXIMUM) mm.
HARDNESS (CANADIAN GAUGE) gr/cm² x 100
DENSITY gr/cm³
1960
1959
1958
1957
1956
1955
1954
1953 (± 1)

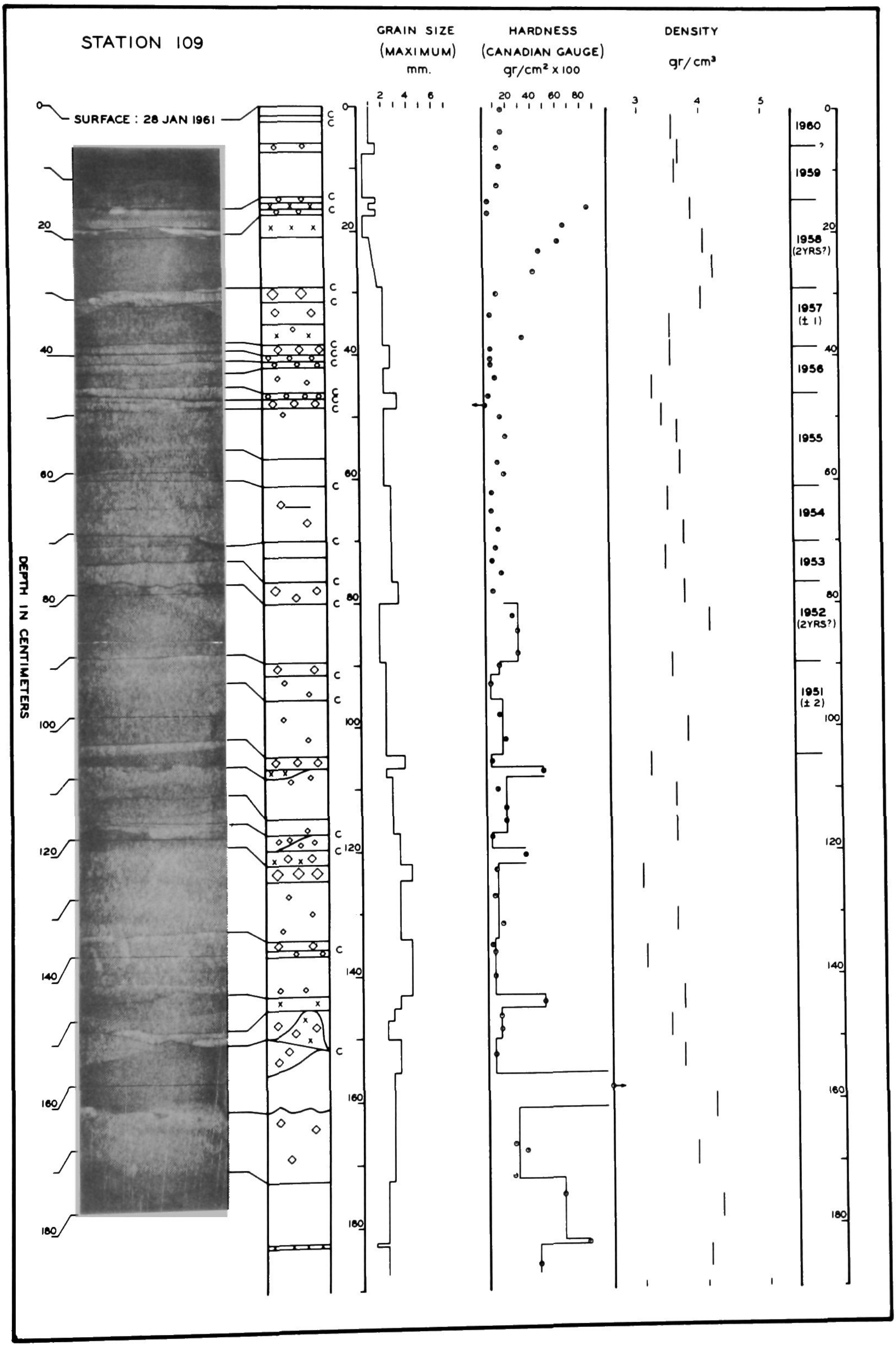


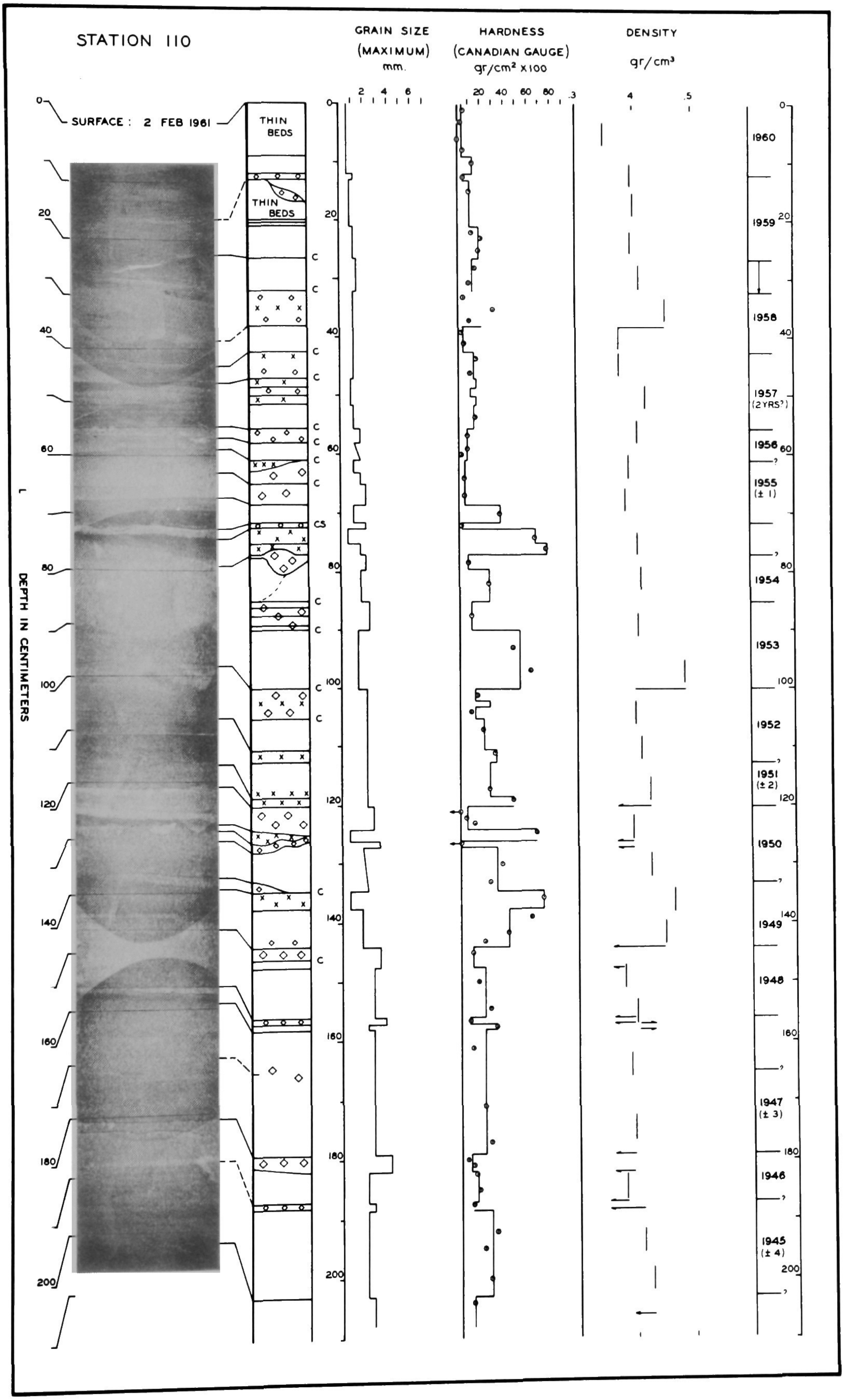
STATION 106
SURFACE: 16 JAN 1962
DEPTH IN CENTIMETERS
GRAIN SIZE (MAXIMUM) mm.
HARDNESS (CANADIAN GAUGE) gr/cm² x100
DENSITY gr/cm³
1960
1959
1958
1957 ±1
1956
2YRS?
1955
1954 ±2
1 YR?
2YRS?
2YRS?


STATION 107
GRAIN SIZE (MAXIMUM) mm.
HARDNESS (CANADIAN GAUGE) gr/cm² x 100
DENSITY gr/cm³
DEPTH IN CENTIMETERS
THIN BEDS
1960
1959
1958
1957 ± 1
1 YR?

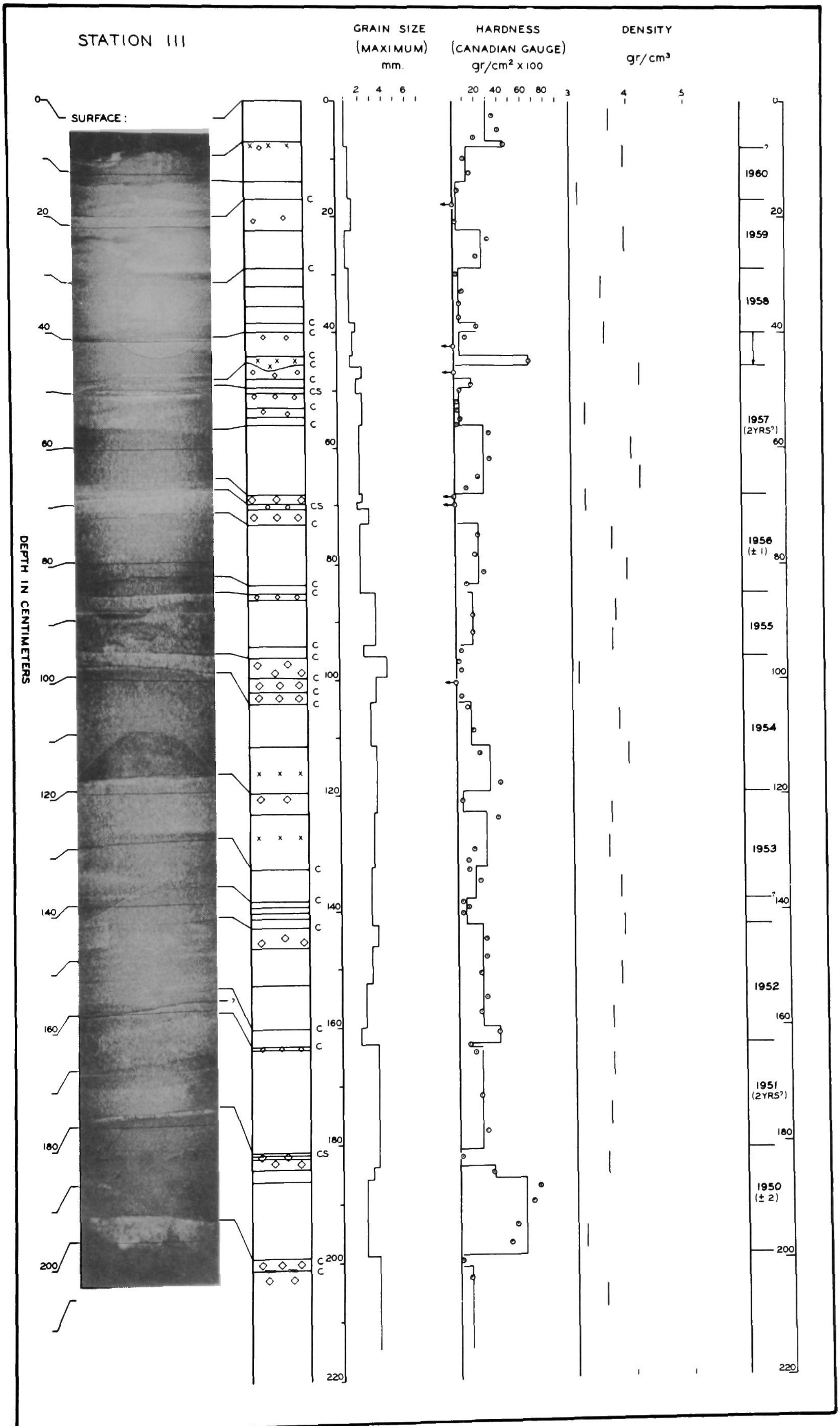


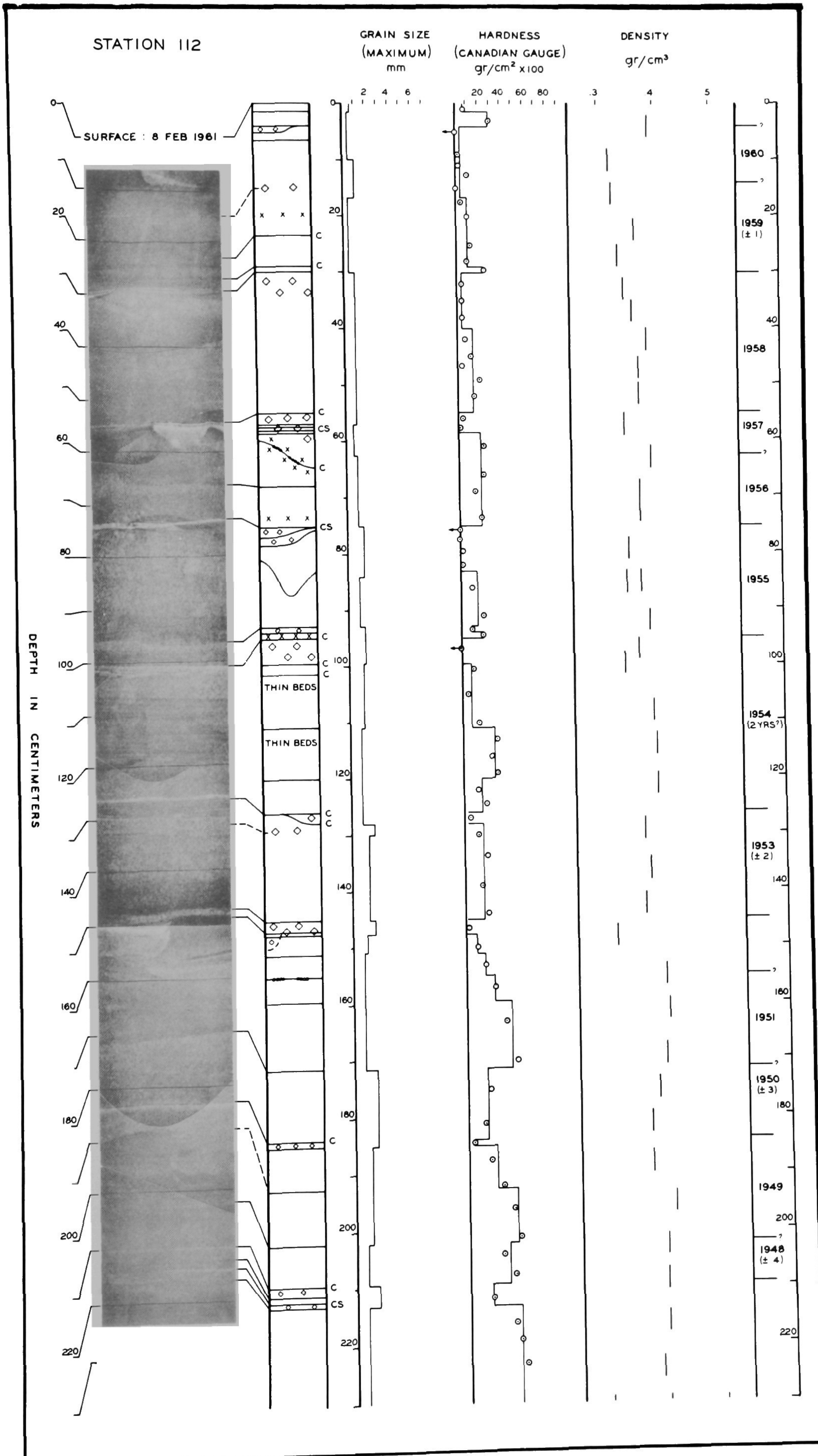
STATION 108
SURFACE: 22 JAN 1962
DEPTH IN CENTIMETERS
GRAIN SIZE (MAXIMUM) mm.
HARDNESS (CANADIAN GAUGE) gr/cm² x 100
DENSITY gr/cm³
1960
1959
1958
1957 (2 YRS?)
1956 (± 1)
1955
1954 (2 YRS?)
1953 (± 2)
1952
1951
1950
1949
1948 (± 3)


STATION 109
GRAIN SIZE (MAXIMUM) mm.
HARDNESS (CANADIAN GAUGE) gr/cm² x 100
DENSITY gr/cm³
SURFACE : 28 JAN 1961
DEPTH IN CENTIMETERS
1960
1959
1958 (2YRS?)
1957 (± 1)
1956
1955
1954
1953
1952 (2YRS?)
1951 (± 2)



STATION 110
SURFACE: 2 FEB 1961
GRAIN SIZE (MAXIMUM) mm.
HARDNESS (CANADIAN GAUGE) gr/cm² x100
DENSITY gr/cm³
THIN BEDS
DEPTH IN CENTIMETERS
1960
1959
1958
1957 (2 YRS?)
1956
1955 (± 1)
1954
1953
1952
1951 (± 2)
1950
1949
1948
1947 (± 3)
1946
1945 (± 4)


STATION III
GRAIN SIZE (MAXIMUM) mm.
HARDNESS (CANADIAN GAUGE) gr/cm² x 100
DENSITY gr/cm³
SURFACE :
DEPTH IN CENTIMETERS
1960
1959
1958
1957 (2 YRS?)
1956 (± 1)
1955
1954
1953
1952
1951 (2 YRS?)
1950 (± 2)



STATION 112
GRAIN SIZE (MAXIMUM) mm
HARDNESS (CANADIAN GAUGE) gr/cm² x100
DENSITY gr/cm³
SURFACE : 8 FEB 1961
DEPTH IN CENTIMETERS
THIN BEDS
THIN BEDS
C
CS
1960
1959 (± 1)
1958
1957
1956
1955
1954 (2 YRS?)
1953 (± 2)
1951
1950 (± 3)
1949
1948 (± 4)